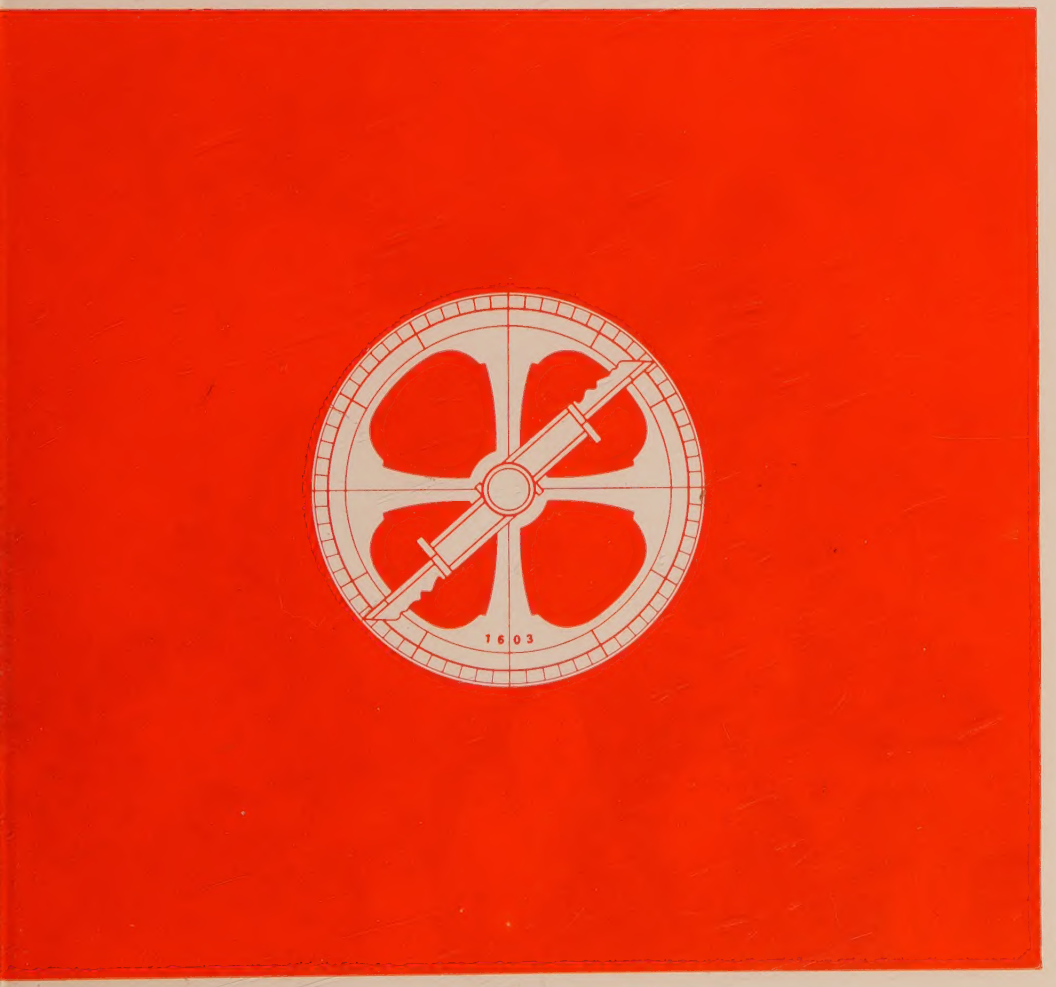
GEOGRAPHICAL BULLETIN

Volume 9 Number 3 1967



GEOGRAPHICAL BRANCH
Department of Energy, Mines and Resources
Ottawa, Canada

GEOGRAPHICAL BRANCH

J. K. Fraser, Acting Director, Geographical Branch
G. Fremlin, Chief of Division, Regional Geography
O. H. Løken, Chief of Division, Physical Geography
Margaret Montgomery Larnder — *Editor*
Joyce Howes — *Associate Editor*
Monika Pent — *Assistant to the Editor*

Cartography under supervision of Rolande Trevor

EDITORIAL ADVISORY BOARD

J. W. Birch	Toronto
Ivor Bowen	Ottawa
Marjorie Bursa	Montreal
Reid A. Bryson	Madison, Wis.
Ian Burton	Toronto
Pierre Camu	Ottawa
Keith Clayton	London, England
J. A. Elson	Montreal
Richard Foster Flint	New Haven, Conn.
L.-E. Hamelin	Quebec
N. L. Nicholson	London, Ontario
J. Lewis Robinson	Vancouver
Diana M. R. Rowley	Ottawa
Morley K. Thomas	Toronto

NOTICE

THIS VOLUME IS INCOMPLETE

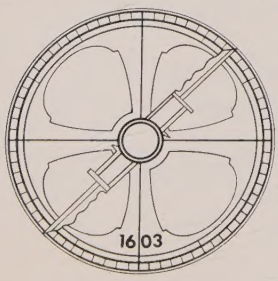
THE FOLLOWING ISSUES ARE ON ORDER:

Vol. 8	No. 3	1966
	No. 4	1966
Vol. 9	No. 1	1967
	No. 2	1967

GEOGRAPHICAL BULLETIN

Champlain's astrolabe, lost near the Ottawa River in 1613 and found in August 1867, has been adopted as the symbol of the Geographical Branch. Appointed Geographer to the King of France in 1603, Samuel de Champlain is thus recognized as the forefather of Canadian geography.

The statue of Champlain stands on Nepean Point, Ottawa. The sculptor has used a degree of artistic license in that the astrolabe is held upside down.



Digitized by the Internet Archive
in 2024

https://archive.org/details/geographical-bulletin_1967_9_3

CONTENTS TABLE DES MATIÈRES

Requiem or Renaissance? ..... *J. Keith Fraser* i

Development, landforms and chronology of Generator Lake, Baffin Island, N.W.T. ..... *D. M. Barnett* 169

Les pingos de l'île Prince Patrick (76°N – 120°W) .. *A. Pissart* 189

The influence of pleistocene climatic changes on the development of the polygenetic pediments in the Cypress Hills area, Alberta ..... *P. D. Jungerius* 218

Hydrology of the Lewis Glacier, North Central Baffin Island, N.W.T., and discussion of reliability of the measurements *Anonymous* 232

Notes

Fluvial processes in the high Arctic ..... *Frank Cook* 262

Reduced values of solar radiation with occurrence of dense smoke over the Canadian tundra ..... *James T. Peterson and L. D. Drury* 269

Use of floor space in the functional differentiation of small towns ..... *Charles A. Hutton* 272

Early settlement about Medicine Hat, Alberta ..... *R. Common* 284

Grants awarded by the National Advisory Committee on Geographical Research for 1968-69 294

Book Review 296

© Crown Copyrights reserved

Requests for the *Geographical Bulletin* should be directed to the Queen's Printer, Ottawa, Canada.

Les commandes pour le *Geographical Bulletin* doivent être adressées à l'Imprimeur de la Reine, Ottawa, Canada.

Published quarterly

Single copies $3.50 Subscription rate $10.00 per year

Catalogue No. M65-1/9-3

ROGER DUHAMEL, F.R.S.C.
Queen's Printer and Controller of Stationery
Ottawa, Canada, 1967

Cover design and symbol/Dessin de la couverture et du symbole: George Falconer and/et Hania Guzewska.

Geography is the scientific study of a highly evolved complex – the man-land relationship; and such a study is so intimately bound up with social and economic structure that relevance to national needs ought to be a major determinant in one's choice of research.

Quote from F. K. Hare
Canadian Geographer
VIII(3) 1964 p. 113.

REQUIEM OR RENAISSANCE?

The appearance of this issue of the *Geographical Bulletin* coincides with the termination of the Geographical Branch after nearly 21 years of research and publication. During a period when academic geography in Canada increased from only three university departments in 1947 to over two dozen in 1967, the Geographical Branch provided a focus for national programs of geographic activity and a training ground for many undergraduates and graduates of the expanding university departments.

This editorial is neither a history of the Geographical Branch nor an attempt to defend the decision to dissolve it. Nevertheless, an explanation is due to subscribers to the *Geographical Bulletin*. A brief glance at the role of the Branch in the federal government is necessary to understand how it had developed and why it was terminated. This is also an opportunity to inform the geographical community about the disposition of the various components of the Branch.

Established in 1947, the Geographical Branch was originally conceived as an intelligence service, charged with providing geographical information on foreign countries and Arctic Canada. The first objective resulted in a number of reports on selected critical areas in which Canada had trade interests or had assumed certain responsibilities through the United Nations. Though well received, these reports had little publicity due to their restricted circulation. As the emphasis on Canadian geography increased, the foreign geography section lost its importance and was discontinued in 1960.

The collection of basic information on the Canadian Arctic, however, was given high priority from the beginning and developed from the early reconnaissance surveys into the multi-disciplinary research program on Baffin Island and the less ambitious geomorphological studies of the Mackenzie Delta region. Terrain analysis, particularly through the preparation of air photo interpretation keys, was carried out in selected areas in the archipelago and along the mainland coasts of Arctic Canada. Concurrently, regional intelligence reports were produced in the office. Geographers participated in the evaluation of DEW Line sites and the selection of the site of Inuvik, and were assigned as observers on the Eastern Arctic Patrol.

The impetus for a high proportion of the projects undertaken by the Branch, especially in its formative years, was derived from other government agencies. Though field research was not envisaged in the original terms of reference, it was soon recognized that the assemblage of information from existing sources was inadequate. Programs developed through the initiative of the staff included the systematic airborne survey of ice distribution in the Gulf of St. Lawrence and the Canadian Arctic Archipelago, the exploration of the newly discovered islands in Foxe Basin and the production of the

first national atlas of Canada since 1915. Nevertheless, to the end, much of the research program was derived from and dependent on the needs and support of other government departments.

In response to a request from the World Land Use Commission of the International Geographical Union, the Branch became involved in land use studies as early as 1950. These were expanded, especially in the Maritimes, in collaboration with ARDA and involved both field surveys and photo interpretation of rural land characteristics. Urban studies evolved out of civil defence projects. In more recent years, regional economic studies were conducted for ARDA and the Atlantic Development Board.

It was recognized early that a professional journal was necessary to make public the results of field and office research. The *Geographical Bulletin* first appeared in 1951 and was published on an irregular basis, usually twice yearly, until 1965 when it became a quarterly. Complementing the *Bulletin* were the *Geographical Papers* series, designed to present individual reports and used successfully to publish the results of the annual ice distribution surveys; the *Geographical Memoirs*, a number of regional monographs; the *Bibliographical Series*, providing cumulative or selective bibliographies on Canadian geography; the *Gazetteer of Canada;* and the *Geographical Information Series.*

In 1966, the Department of Energy, Mines and Resources was created, combining Mines and Technical Surveys with parts of Northern Affairs and National Resources and various Crown Corporations. This extensive reorganization, which included the establishment of several new branches concerned with advising and implementing government policy in the field of national resources, particularly that of water, resulted in a close examination of the role of geographers in the new departmental context. The decision was taken in early 1967 that geographers with their training and outlook could be employed to greater advantage by incorporating them among the other specialized branches. As of April 1, 1968, the Geographical Branch came to an end as a discrete entity.

It is not uncommon for governmental reorganization to result in the termination of an established agency. Rather, it is surprising that in a field as diffuse as geography, an institution created primarily to collect and collate geographical intelligence on foreign countries and northern Canada should have expanded and persisted for over twenty years during a period of such dynamic change.

Most of the geographers in the Division of Physical Geography were transferred to the Geological Survey, where they and the former Pleistocene Geology Section become the Division of Quaternary Geology and Geomorphology. Those specializing to a greater extent in glaciology were assigned to the Glaciology Subdivision in Inland Waters Branch.

The economic geographers who were concerned with land use mapping and regional economic studies have been transferred to Policy and Planning Branch where they form the nucleus of a new Economic Geography Section in the Resources Research Centre. In the same branch, provision was made for a secretariat to serve the National Advisory Committee on Geographical Research and the Canadian National Committee of the International Geographical Union. The Geographical Branch book library is administered by Policy and Planning Branch as the basis of an expanding library to serve the Water Sector of the Department.

The geographers and cartographers involved in the production and revision of the National Atlas of Canada now form the Thematic Mapping Section in Surveys and Mapping Branch. This Branch will also administer the Departmental Map Library. The Division of Toponymy, responsible for the production of gazetteers and the stand-

ardization of geographical names, is transferred to Surveys and Mapping Branch, becoming the Secretariat of the Canadian Permanent Committee on Geographical Names.

Considerable attention was given to the problem of maintaining publication of the *Geographical Bulletin* within the Department or under the aegis of the Canadian Association of Geographers. It became evident that none of the other branches could successfully continue its publication along the lines already developed. It was also apparent that editorial problems and costs would not allow the Canadian Association of Geographers to produce the *Bulletin* in addition to their own periodical. The Department, therefore, has taken steps to increase the annual grant which will permit the Association to expand and improve the publication of geographical material.

It was desirable that all papers on hand should be published before the *Geographical Bulletin* suspended publication. This will be accomplished by this issue, significantly larger than any previous number. To complete Volume 9, Number 4 will be a special issue composed of reprints from the four major professional geographical periodicals in Canada. As well as being the final issue of the Geographical Bulletin, it will also be distributed at the 21st International Geographical Congress in New Delhi in December, 1968, as the display publication for Canadian geography.

In writing this editorial, I prefer not to look on it as a requiem for the Geographical Branch or the *Geographical Bulletin*, but rather to take the point of view that the dispersement of geographers throughout the Department will result in a renaissance of geographical research. It is the regional approach rather than the subject matter of geography that differentiates it from other disciplines. The new emphasis on policy making in the Department should allow greater scope for the application of the regional approach and it is already evident that projects such as the National Atlas of Canada, the regional economic studies and the various aspects of research in the Arctic are receiving enthusiastic support in their new environments.

J. Keith Fraser,
Acting Director,
Geographical Branch.

Le géographe, qui n'a certainement pas le monople de la sagesse et de la compétence dans l'aménagement régional et dans le développement, a tout de même un rôle essentiel et irremplaçable qui se situe du côté des aspects spatiaux des problèmes.

Cité de Fernand Grenier
Canadian Geographer
IX(3) 1965 pp. 120-121.

REQUIEM OU RENAISSANCE?

La parution de ce numéro du *Geographical Bulletin* coïncide avec la disparition de la Direction de la géographie après plus de 20 années de recherches et de publication. Au cours d'une période où l'enseignement supérieur de la géographie au Canada a pris une expansion telle que le nombre de départements de géographie est passé de trois en 1947 à plus de vingt-quatre en 1967 dans les universités canadiennes, la Direction de la géographie a constitué un point de mire pour des fonctions géographiques nationales et a servi de centre de formation aux étudiants et diplômés des départements de géographie.

Cet éditorial ne vise pas à faire l'historique de la Direction de la géographie, ni ne cherche à défendre la décision qui a amené sa dissolution. Toutefois, les lecteurs du *Geographical Bulletin* on droit à une explication. Un bref rappel du rôle de la Direction au sein du gouvernement fédéral est nécessaire, si l'on veut comprendre de quelle manière elle a pris de l'expansion, et connaître les raisons de sa dissolution. Le présent éditorial nous fournit aussi une occasion dc renseigner les géographes sur l'affectation des divers effectifs de la Direction.

Créée en 1947, la Direction de la géographie a d'abord été conçue comme service de renseignements chargé de fournir des informations d'ordre géographique sur les pays étrangers et sur l'Arctique canadien. Dans la poursuite du premier objectif, la Direction a présenté un certain nombre de rapports sur des régions stratégiques dans lesquelles le Canada avait des intérêts commerciaux ou avait assumé certaines responsabilités sous les auspices des Nations Unies. Bien que favorablement accueillis, ces rapports ont reçu peu de publicité à cause de leur circulation réduite. A mesure que la géographie du Canada prenait de l'importance, la Section de géographie étrangère était reléguée à l'arrière-plan, si bien que ses activités cessèrent définitivement en 1960.

On a toutefois accordé dès le début une très grande importance au recueil de données fondamentales sur l'Arctique canadien. Ce travail a passé des levés de reconnaissance à la programme de recherches multi-disciplinaire de l'île Baffin et des études géomorphologiques moins ambitieuses de la région du delta du Mackenzie. Grâce surtout à la préparation de clés d'interprétation des photos aériennes, des analyses du terrain ont été effectuées dans des régions choisies de l'Archipel arctique et le long des côtes de l'Arctique canadien. Concurremment, des rapports de renseignements régionaux étaient rédigés à la Direction. Les géographes ont participé à l'évaluation du réseau de postes de la ligne DEW et au choix de l'emplacement d'Inuvik, et ils ont été affectés comme observateur dans la patrouille de l'Arctique oriental.

Particulièrement au cours des premières années, l'initiative d'une grande partie des

travaux entrepris par la Direction est venue d'autre ministères ou agences du gouvernement. Bien que la recherche sur le terrain n'eût pas été considérée dans les attributions initiales de la Direction, on se rendit bientôt compte que le rassemblement des données provenant des sources existantes était inadéquat. Le personnel de la Direction a pris l'initiative d'élaborer certains programmes, dont le relevé aérien systématique de la répartition des glaces dans le golfe Saint-Laurent et l'Archipel arctique canadien, l'exploration des îles récemment découvertes dans le bassin Foxe et la publication du premier Atlas du Canada depuis 1915. Néanmoins, jusqu'à la fin, une grande partie du programme de recherches était conçue en fonction des besoins et avec la collaboration d'autres ministères du gouvernement.

En réponse à une demande de la Commission sur l'utilisation du sol dans le monde, de l'Union géographique internationale, la Direction participa à des études de l'utilisation des sols dès 1950. Ces études ont pris de l'ampleur, particulièrement dans les Maritimes, en collaboration avec l'ARDA, et ont nécessité des levés sur le terrain et l'interprétation photogrammétrique des terres rurales. Les entreprises de défense civile ont aussi occasionné des études sur les agglomérations urbaines. Plus récemment, des études d'économie régionale ont été effectuées pour le compte de l'ARDA et de l'Office d'expansion économique de la région de l'Atlantique.

La nécessité d'une revue professionnelle se fit bientôt sentir comme moyen de diffuser les résultats des recherches effectués sur le terrain et au bureau. Le *Geographical Bulletin* a d'abord paru en 1951 et a été publié ensuite à des intervalles irréguliers, à l'ordinaire deux fois par année, jusqu'en 1965, alors que la revue est devenue une publication trimestrielle. Le *Bulletin* a été complété par la série des *Geographical Papers,* publiée dans le but de présenter des rapports individuels et qui a servi efficacement à la publication des résultats des relevés annuels de la répartition des glaces; par les *Geographical Memoirs,* comprenant un certain nombre de monographies régionales; par la *Bibliographical Series* qui a fourni des bibliographies cumulatives ou sélectives sur la géographie du Canada; par la série des *Répertoires des noms géographiques du Canada* et les numéros du *Geographical Information Series.*

Le Ministère de l'Energie, des Mines et des Ressources a été créé en 1966: il réunissait le Ministère des Mines et des Relevés techniques et certaines parties du Ministère du Nord canadien et des Ressources nationales, de même que diverses Sociétés de la Couronne. Cette importante réorganisation, qui comprenait la création de quelques Directions chargées de conseiller le gouvernement et de mettre en œuvre ses politiques relatives aux ressources nationales, particulièrement les ressources hydriques, a donné lieu à une étude approfondie du rôle des géographes dans le nouveau contexte du Ministère. Au début de 1967, il fut décidé que la formation et la compétence des géographes seraient mieux utilisées s'ils étaient intégrés dans d'autres Directions spécialisées. Le premier avril 1968, la Direction de la géographie arriva à son terme.

Il n'est pas exceptionnel que les réorganisations gouvernementales entraînent la dissolution d'un organisme existant. Il est plutôt surprenant que dans un domaine aussi diversifié que la géographie, un organisme créé d'abord pour rassembler des renseignements géographiques sur les pays étrangers et sur le Canada septentrional ait pris de l'expansion et ait vécu pendant plus de vingt années durant une période où des changements si dynamiques ont eu lieu.

La plupart des géographes de la Division de la géographie physique sont passés à la Commission géologique, où avec l'ancienne Section de la géologie du Pléistocène, ils formeront la Division du Quaternaire et de la géomorphologie. Les géographes qui se spécialisaient plus particulièrement en glaciologie ont été affectés à la Sous-division de la glaciologie de la Direction des eaux intérieures.

Les spécialistes de la géographie économique qui s'occupaient de dresser les cartes de l'utilisation des sols et des études économiques régionales sont passés à la Direction de la planification où ils forment le noyau d'une nouvelle Section de la géographie économique au Centre de recherches sur les ressources. Au sein de la même Direction, on a pris les dispositions nécessaires à la création d'un secrétariat qui sera mis au service du Comité consultatif national de la recherche géographique et du Comité national canadien de l'Union géographique internationale. La Direction de la planification administre la bibliothèque de la Direction de la géographie, qui servira de base à l'établissement d'une bibliothèque plus complète répondant aux besoins du Secteur de l'eau du Ministère.

Les géographes et les cartographes qui travaillent à la revision de l'Atlas du Canada forment maintenant la Section de la cartographie thématique de la Direction des levés et de la cartographie. Cette Direction administrera aussi la Cartothèque du Ministère. La Division de la toponymie, chargée de la production des Répertoires des noms géographiques et de la normalisation des noms de lieu, passe à la Direction des levés et de la cartographie et jouera le rôle de Secrétariat du Comité permanent canadien des noms géographiques.

On a réfléchi sérieusement à la possibilité de continuer à publier le *Geographical Bulletin* au sein du Ministère ou sous l'égide de l'Association canadienne des géographes. Il est devenu évident qu'aucune autre Direction ne pourrait poursuivre avec succès la publication de cette revue en suivant l'orientation qui lui avait déjà été donnée. En outre, comme il semblait que les problèmes éditoriaux et les coûts de production ne permettraient pas à l'Association canadienne des géographes de publier le *Bulletin* en plus de leur propre revue, le Ministère a décidé d'accroître sa subvention annuelle à l'Association dans le but de la permettre l'expansion de la publication d'études géographiques.

Il était souhaitable que tous les rapports déjà soumis soient publiés avant que cesse la publication du *Geographical Bulletin*. Ils feront donc partie du présent numéro qui est beaucoup plus grand que les numéros antérieurs. Le quatrième numéro du Volume 9 sera un numéro spécial composé de réimpressions des quatre principales revues géographiques professionnelles au Canada. En plus d'être le dernier numéro du *Geographical Bulletin,* il sera aussi distribué comme publication type de la géographie canadienne lors du 21e Congrès géographique international qui sera tenu en décembre 1968.

En écrivant cet éditorial, je ne le considère pas comme un requiem pour la Direction de la géographie ou le *Geographical Bulletin*, mais je pense plutôt que la dispersion des géographes au sein du Ministère entraînera une renaissance de la recherche géographique. La différence entre la géographie et les autres disciplines se situe dans son optique régionale plutôt que dans son sujet. La nouvelle importance accordée à la formulation des politiques au sein du Ministère devrait permettre une plus grande place à la façon d'aborder les problèmes par région et il est manifeste dès maintenant que des projets comme la publication de l'Atlas du Canada, les études économiques régionales et les divers aspects de la recherche dans l'Arctique reçoivent un accueil enthousiaste dans leur nouveau milieux.

J. Keith Fraser,
Directeur intérimaire,
Direction de la géographie.

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 169–188, 1967

DEVELOPMENT, LANDFORMS AND CHRONOLOGY OF GENERATOR LAKE, BAFFIN ISLAND, N.W.T.*

D. M. Barnett

ABSTRACT

The development of Generator Lake is traced from its beginnings as a proglacial lake ponding against the regional watershed to a lake with an area of some 120 km^2 still dammed by part of the Barnes Ice Cap after a 26-km retreat of the ice margin. Further retreat resulted in the draining of the lake by a new outlet into the Clyde River and a fall in lake level of 75 metres. The trend of net retreat has continued for another 5 km to the present ice cliffs and, since 1948, the average rate of retreat has been 25 metres per year. The present ice cliffs stand more than 17 metres above water level at their highest point. A description is given of the following assemblage of landforms, developed in the proglacial lake environment and exposed when the former lake drained: the shoreline, ice-pushed ridges, deltas, cross-valley moraines and a terrace. The stratigraphic relationship between the last two suggests a subglacial origin for the moraines. A similar set of landforms are developing in the present lake. A critical review of lichenometry indicates that caution is necessary when applying this useful dating technique close to the size limit of a species. A provisional chronology covering the last 1,500 years is proposed, extending from establishment of the higher lake between 1,500 and 1,100 years ago to its draining between 950 and 750 years ago. Careful levelling of the shoreline indicates that it is not measurably deformed.

RÉSUMÉ

L'histoire de l'évolution du lac Generator le montre à ses débuts comme un lac proglaciaire formant retenue des eaux d'écoulement régionales; par la suite il est devenu un lac d'une superficie d'environ 120 km^2 encore endigué par une partie de la calotte glaciaire Barnes, après un recul de 26 km de la rive du glacier. Un recul plus poussé a eu pour résultat l'écoulement des eaux du lac par une nouvelle décharge dans la rivière Clyde et la baisse de 75 m du niveau du lac. Le recul net s'est poursuivi sur 5 km de plus jusqu'aux escarpements de glace actuels; depuis 1948, l'allure moyenne du retrait est de 25 mètres par an. Ces escarpements sont à plus de 17 mètres au-dessus du niveau de l'eau à leur point le plus élevé. L'auteur donne une description de l'assemblage des formes de relief qui se sont développées dans le milieu ambiant du lac proglaciaire et ont été mises à nu lorsque l'ancien lac a drainé la rive, les arêtes poussées par la glace, les deltas, les moraines transversales et une terrasse. La relation stratigraphique entre les deux dernières évoque une origine sous-glaciaire pour les moraines. Un assortiment similaire de formes de relief est en voie de formation dans le lac actuel. Un examen attentif de la «lichénométrie» indique qu'il faut être prudent quand on emploie cette technique de datation et s'en tenir à la grosseur limite d'une espèce. L'auteur propose une chronologie provisoire embrassant les 1,500 dernières années. Elle s'étend depuis l'établissement du lac supérieur, datant de 1,500 à 1,100 ans, jusqu'à son assèchement datant de 950 à 750 ans. Un nivellement soigné de la rive prouve qu'elle n'est pas sensiblement déformée.

MS submitted June, 1967.

*A shorter paper based on some of this work was presented at the meeting of the Canadian Association of Geographers in Sherbrooke, Quebec, May 1966.

INTRODUCTION

This paper is based on observations made during parts of the 1965 and 1966 field seasons. More detailed work and other papers are planned or in preparation, for example, a paper on echo sounding of the present lake elaborating on some of the problems outlined here.

Generator Lake is one of several proglacial lakes located at the margin of the Barnes Ice Cap and lies in north-central Baffin Island on the interior upland termed by Bird (1967, p. 62) the *Baffin Surface*. The ice cap has disrupted the drainage of the area and impounded several lakes such as Conn and Bieler in the northeast – the largest existing proglacial lakes in North America. Other large proglacial lakes, now drained, existed formerly around the ice margin (Ives, 1962, p. 199, Andrews, 1965), and thus a detailed study of one which is only partially drained offers an unusual opportunity for comparative studies of the changing proglacial environment (*see* Price, 1965).

In 1950 the Arctic Institute Baffin Island Expedition had a major camp (A2) at the southwest corner of the most southeasterly of the impounded lakes to which they gave the name Generator Lake (Baird, *et al.*, 1950). Subsequently, Goldthwait (1951) wrote a major paper on the development of nearby end moraines and later Weertman (1961) considered them theoretically. The work reported here represents the first effort directed to studying the landforms and chronology of the lake basin itself. As the lake is proglacial, the characteristics of that part of the Barnes Ice Cap damming it must be considered as an integral part of the study.

THE GEOGRAPHICAL SETTING

Generator Lake (69°33′ N 71°45′W) (Figure 1) is located at the southeastern margin of the Barnes Ice Cap at an elevation of approximately 400 metres. It lies in a southwestward sloping valley very close to the present drainage divide from which the rivers draining from the southern limit of the ice cap flow east, west and south. The source of the eastward flowing Clyde River is the overflow waters of Generator Lake. Earlier the lake basin had been the preglacial headwater of a southwestward flowing stream that formerly drained into Foxe Basin by way of Flyway Lake and Flint Lake. The subglacial topography of the ice dam was first shown by gravimetric profiles obtained by Littlewood (1952, p. 123), and data on the sub-lacustrine morphology obtained by the present writer confirm this postulated former drainage route.

The present lake has maximum dimensions of 13.5 km by 6.5 km and drains approximately 410 km^2 of ice-free land as well as a portion of the Barnes Ice Cap. The shoreline of the lake is extremely crenulate as partially emerged cross-valley moraines severely indent the eastern two-thirds of its shoreline (Figures 1 and 2). These moraines are similar to those studied in detail and described by Andrews (1963a, 1963b) and by Andrews and Smithson (1966). In the northeast part of the lake basin, drainage is locally impounded between individual cross-valley moraines to form elongate ponds, with the occasional narrow breach in the moraine maintaining the drainage system. The Clyde River is the only outlet of the present lake.

DEVELOPMENT OF GENERATOR LAKE

THE FORMER LAKE

In the subsequent discussion of the lake phases it is essential to keep in mind its proglacial origin, as its area and depth at any given time depend upon the location of the ice margin at that period and on the position of low points in the watershed. In general, the lake progressively increased in area and depth as the retaining ice-barrier retreated southwestward, down valley. This general trend was reversed whenever a lower col was uncovered to form a new overflow channel. In the case of the present outlet this process has resulted in a decrease in depth of some 75 metres. Continuing retreat of the present ice margin would lead to the draining of the lake and to the re-establishment of the former southwestern drainage route into Foxe Basin.

The initial phase in the development of the lake was the ponding of meltwater in the extreme northeastern area of the lake basin, adjacent to the watershed (Figure 1). Either concurrently or probably shortly after this initial ponding at least one other small higher level lake (*A* in Figure 1) was ponded against

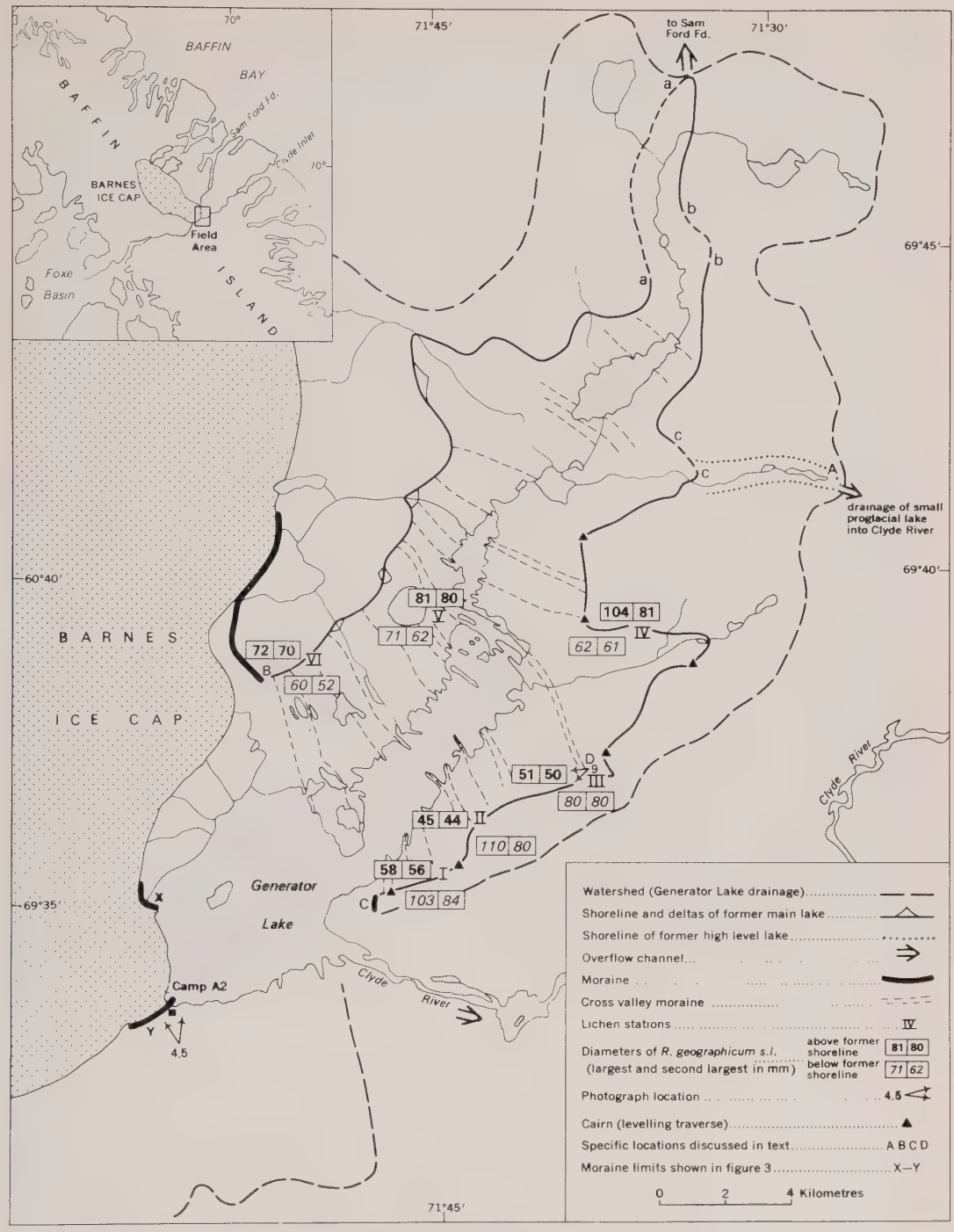


FIGURE 1. Generator Lake drainage basin showing the former and present extent of the lake.

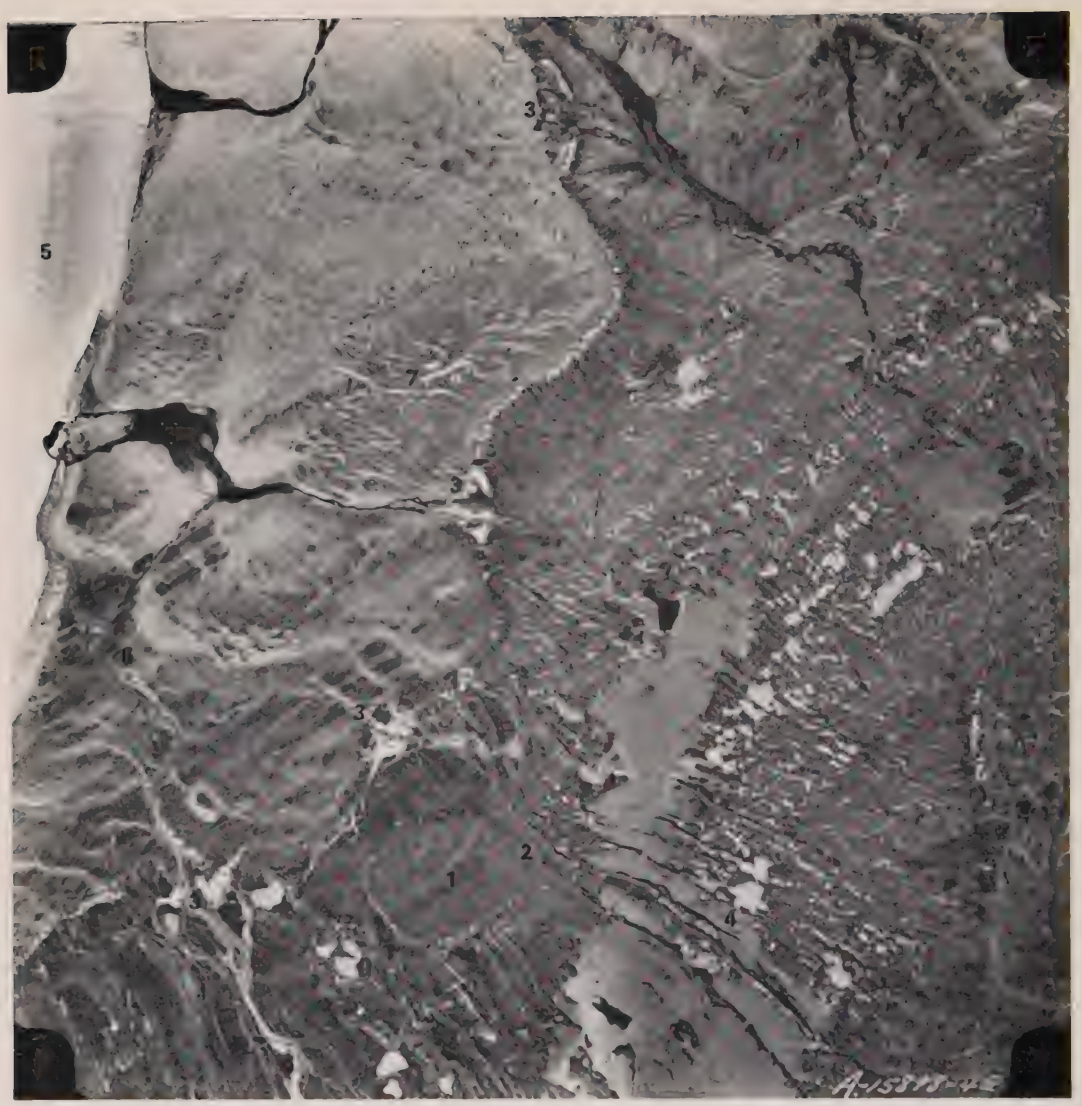


FIGURE 2. Part of air photograph A15898-45 (21,500 ft. 6 in. lens)—(1) the island in the former lake, (2) ice-pushed ridge, (3) deltas of the former lake, (4) cross-valley moraine, (5) Barnes Ice Cap, (6) glacial lineations, (7) glacial drainage channels.

the ice margin in a tributary valley some 15 metres above the main lake level. Evidence for this small high level lake take the form of small marginal sand deposits and a small but well-defined overflow channel which carried its discharge into the Clyde valley. After an 11-km down valley retreat of the ice dam, the smaller lake must have drained into the main one which, at this stage, was increasing in width and depth.

The former Generator Lake, with an area of 120 km^2 at its greatest extent, was larger than the present one. Close to its northern shore was a nearly circular island which is now "dry" though it stands out remarkably well on air photographs (Figure 2) as does the prominent former main shoreline. The extent of this shoreline, shown on Figure 1, marks a level of the lake 75 metres above the present lake surface.

At the maximum extent of the former lake, the shoreline at *B* (Figure 1) reached to within one km of the present ice margin where it terminates abruptly. On the south side of the lake at *C* the shoreline becomes progressively less distinct and finally disappears some 5 km from the ice margin. This termination marks both the former extent of the lake and the position of the ice dam. From the present ice margin where retreat has been negligible a moraine extends down to the old northern shoreline and offers additional supporting evidence for delimiting the maximum extent of the former lake. On the south shore a much less distinct moraine is traceable above the shoreline though it is not possible to follow it any farther than indicated at *C*.

Above the shoreline other specific phases in the 26-km retreat from the watershed are not well marked, though to the northwest of the upper end of the lake some former ice marginal drainage channels are visible (Figure 2, no. 7); to the south a small ill-defined moraine (not shown) may indicate another phase. Below the former shoreline, evidence for phases of retreat is much more apparent. Although the numerous cross-valley moraines mark such phases, their exact relationship to the ice margin is, as yet, unproven.

During the evolution of the lake the shoreline was metachronous, though during any pause at its maximum extent its morphology may have been synchronously modified. These facts have significance when lichenometry is considered as a basis for chronology.

Drainage of the lake

The overflow water of the former lake spilled out at the head of the valley into the Sam Ford River system. The shoreline is traceable right up to the overflow channel though its morphological development is weak at some points (Figure 1 a . . . a, b . . . b, c . . . c).

With the progressive retreat of the ice margin a new outlet via the Clyde River was opened and is still the drainage route used. Morphological evidence for this is supported by the occurrence of outwash along the north side of the Clyde River valley, where the first drainage breakthrough would have occurred. Much of the outwash stands several metres above the present river level, though it is not possible to say how much of this height difference is due to down-cutting of the former watershed and how much to deposition during the fall in level of the lake. However, lack of contrary evidence between the former and present shorelines, suggests that the fall in level was rapid.

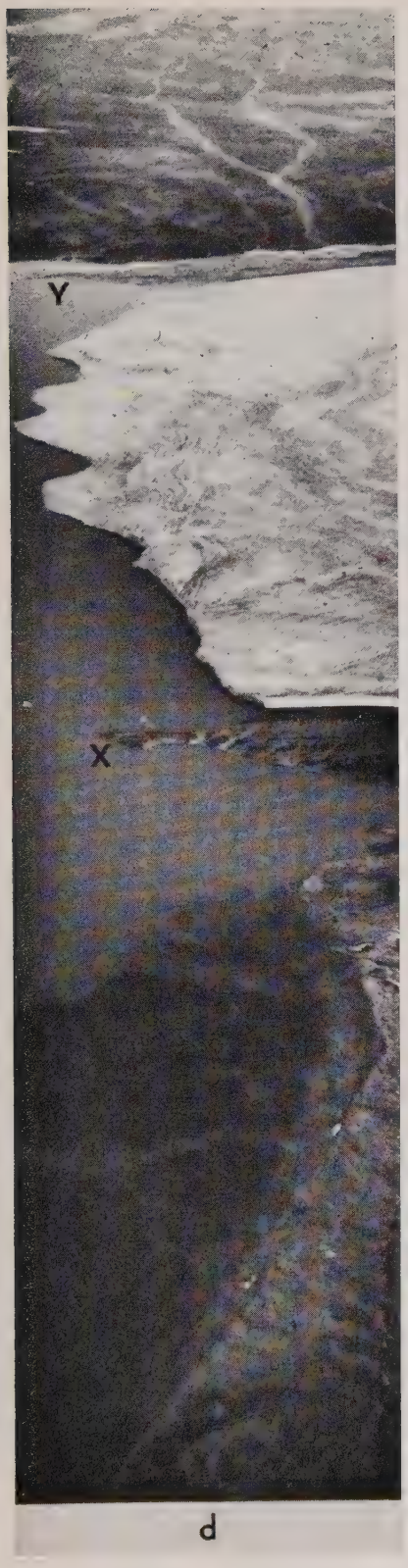
No evidence was found for the draining and re-establishment of the former lake at the same level. The only other possible drainage route is the preglacial one via Flyway Lake, yet Løken and Andrews (1966, p. 350) conclude that the Ice Cap has persisted since the Wisconsin maximum. Hence it is assumed that, despite minor fluctuations of the ice margin, the lake only drained to its present level once.

The present lake and the adjacent ice margin

Initially, the drop in lake level resulting from the breakthrough into the Clyde River valley drastically decreased the lake volume, though subsequently, as the ice cliffs have receded another 5 km, this volume has been increasing. On air photographs flown at different dates, the island in the main body of the present lake shows evidence of differing degrees of submergence, but this is probably due to annual variations in lake level. Ward (1959, p. 437) reported a rise in level of about 0.6 metre in mid-July, 1950, and in 1966 a rise of 0.7 metre was noted between the first formation of a shore lead and July 14. In both 1965 and 1966 a fall in level of the same magnitude was observed by the third week in August despite the strong contrast between the warm weather of 1966 and the cool weather of 1965. The difference in mean temperature anomaly for August was 5°C (9°F) (*Monthly Record: Temperature Anomaly Maps*). This suggests that the annual variation of water level is not primarily controlled by temperature.

The estimated mean net retreat of the ice cliffs was between 5 and 7 metres per year from the time of the draining of the former lake to 1948 (*see* chronology section). Since the initial air photography in 1948, the rate of retreat of the ice cliffs is well documented by subsequent photography in 1960 and 1961 and a much more rapid rate of retreat is indicated (Figure 3a (1948) and 3b (1961)). Moreover, near-vertical photographs taken from a helicopter by a hand-held camera in August 1966

a b c



show further substantial retreat (Figure 3c and 3d). The retreat between 1948 and 1966 was approximately 400 metres, an average rate of almost 25 metres per year. Annual change, however, is erratic. For example, photographs (not shown) indicate a retreat of 90 metres at the northern end of the ice cliffs between June 30, 1960 and July 19, 1961.

The morphology of the ice cliffs has also changed in the past two decades. A photograph of the ice cliffs taken by Montgomery Ritchie of the 1950 Arctic Institute Expedition (Rand Corp., Figure 37) bears the caption "100 foot ice cliffs" probably a visual estimate only. Measurements made from a stereo pair of the 1948 air photographs give a maximum cliff height of 17.5 metres above lake (57 ft) (Mizerovsky, personal communication, 1966). In 1965 the highest cliff measured 17.2 metres (56 ft) on the helicopter altimeter, with an estimated error of ±5 feet. However, ground photographs (Figures 4 and 5) show the change in morphology and, at the extreme south end, the virtual absence of cliffs in 1965.

LANDFORMS OF THE FORMER LAKE

The shoreline

The shoreline has an observed maximum width of 60 metres, though generally it is less than 10 metres, and its morphological development is variable. In some places the form is etched into bedrock and is clear of depositional material; in other places a sandy beach has been left. The most characteristic form however, is that shown in Figure 6. Close to the original overflow channel where it is oldest, the shoreline is less pronounced than farther to the south and west. This difference in development

FIGURE 3

The ice cliffs damming Generator Lake: (a) in 1948 (part of air photo T219c-173), (b) in 1961 (part of air photo A17042-128), (c) in 1966 (oblique photo from 8,500 ft.) and (d) also in 1966 (oblique photo from 8,500 ft. taken from opposite direction to (c)). Note the retreat of the ice margin between the lateral moraines. Scale of (a) and (b) is 1:35,000, (b) having been enlarged.

FIGURE 4
The ice cliffs photographed from the vicinity of the Arctic Institute Expedition (1950) Camp A2. Photograph taken August, 1950 (courtesy Arctic Institute of North America Library). See also Baird, 1950, photograph p. 140.

FIGURE 5
The ice cliffs photographed from the vicinity of Camp A2, photographed August, 1965. Note that the top block has fallen from the cairn.

FIGURE 6. Former Generator Lake shoreline in vicinity of lichen station I.

is probably attributable to the disparity of fetch between the wide and narrow sections of the former lake.

*Ice-pushed ridges**

Several of these ridges occur just above the shoreline. They are composed of large boulders and reach heights of 2 to 3 metres (Figure 7), thus emphasizing the shoreline morphology.

Ice-pushed ridges occur on part of the eastern shoreline in the central section of the former lake and also on the east shoreline of the "island" (2 on Figure 2), locations that are gently shelving close to shore. As creation of the ridges depends both on the configuration of the shore and on the prevailing wind direction during break-up, no specific distribution pattern is apparent, for break-up, if and when it occurs, can be the result of a single storm with consequent variations in wind direction.

Deltas

Wherever large streams entered the former lake, sandy deltas were built (Figures 1 and 2). The largest and best developed are those located on the lake shore closest to the Ice Cap from which a great amount of the construction material must have come. Two of the larger deltas no longer have any drainage line associated with them and this indicates that the former stream was, at least partially, ice-marginal.

*Term as adopted by Nichols (1952).

FIGURE 7. Ice-pushed ridge above the former shoreline (foreground).

Cross-valley moraines

The occurrence of these striking landforms is restricted to the lake basin below the level of the former shoreline. As observed by Andrews and Smithson (1966, p. 273) in their study of the Isortoq moraines this fact is a major diagnostic characteristic of this type of landform. Another distinct characteristic noted by Andrews (1963a, p. 63) and strongly substantiated by Smithson (1965, p. 72) is the asymmetry of the slope angles of the two sides of this type of landform. Paired slope measurements were made on sixteen moraines in the Generator Lake area in localities where they are distinct in form. Most showed steeper distal slopes, often 10 degrees steeper than their proximal counterparts (Figure 8). Each measurement was based on the mean of two readings, one up and one down the slope. The distal-slope angles ranged between 16 degrees and 32 degrees and the proximal-slope angles between 8 degrees and 27 degrees.

The vertical development of the cross-valley moraines tends to be greater toward the centre of the lake basin than toward the shore. A similar increase in amplitude and definition is apparent between the small moraines in the northeast near the head of the lake basin and the larger moraines in the southwest where the lake was wider and deeper.

Other landforms

A linear, sandy, flat-topped, dissected feature occurs from 2 to 4 metres below the old shoreline on the south side of the former lake (Figure 9). It is tentatively termed a proglacial lake terrace. To date, insufficient work has been done to offer an adequate genetic name for the feature, though it is felt that it may have sufficiently distinctive characteristics to warrant a specific term. Ives (1962, p. 198) has used the descriptive term "kame-delta" for apparently similar features. The valley-side location suggests that it could be either a beach deposit or a kame terrace. In fact Charlesworth (1957,

FIGURE 8. Emerged cross-valley moraines. Note their asymmetry, arcuate shape and best development in the central section. The ice cliffs are to the right.

FIGURE 9
Low level aerial oblique looking west-southwest along the old beach, showing the shoreline and dissected terrace on the south side of Generator Lake. Cross-valley moraines are present below the shoreline though the viewing angle distorts their relief. Note the marked contrast in tone above and below the shoreline (Photo: J. D. Ives).

p. 416) states: "Kame terraces may be easily confused with the strandlines of glacier lakes; the mistake has not infrequently been made." Preliminary work suggests that this feature is neither. Apart from the occasional cobble-size boulder on the surface, it is composed of bedded sands which dip obliquely away both from the shoreline and from the former ice margin.

Grain size analyses of six samples from the terrace, five samples from the abandoned beach and one sample from the present beach of Generator Lake are shown in Figure 10. The five samples from the abandoned beach are paired with terrace samples. Contrast in the degree of sorting, as determined by the Trask sorting coefficient and logarithmic coefficient are shown in Table 1. The logarithmic coefficient, being an arithmetic measure, enables a mean to be calculated for comparative purposes (Krumbein and Pettijohn, 1938, p. 232). Friedman (1962, Table 5, p. 752) has reassessed the class limits of sorting proposed by Trask and would thereby classify the beach sediments as *moderately sorted* and the terrace sediments as *poorly sorted*. The poor degree of sorting implies a glaciofluvial origin. Deposition at the progressively retreating ice cliff where an ice marginal stream enters the lake is a probable explanation of its origin from the evidence currently at hand.

Stratigraphic relationship between two cross-valley moraines and the terrace

The stratigraphic relationship between these two features (at *D* on Figure 1) offers additional evidence for determining their respective origins. At a few localities along the south shore the moraines meet the terrace and at two points excavations were made to expose the junction for several metres. In both cases the sands of the terrace lay stratigraphically above the till of the moraines (Figure 11), the sub-surface boundary between pebble-free sand and stony till being very distinct. This marked stratigraphic relationship indicates the moraine must have formed first. Andrews and Smithson (1966, p. 289) favour two hypotheses for the formation of moraines – either an ice-frontal or in a sub-glacial position only a short distance behind the ice cliffs. In the event then, of moraine formation at the ice front in Generator Lake, contemporaneous lateral deposition of glaciofluvial material could be expected. This does not appear to have occurred and the evidence is therefore more in favour of the sub-glacial hypothesis.

Table 1

Sorting coefficients of grain size analyses

Morphological form	Laboratory number	Trask sorting coefficient	Logarithmic coefficient
"Proglacial lake terrace"	GBL 2001	1.95	0.290
*"Proglacial lake terrace"	GBL 2002	2.92	0.465
*"Proglacial lake terrace"	GBL 2007	1.78	0.250
*"Proglacial lake terrace"	GBL 2009	2.13	0.328
*"Proglacial lake terrace"	GBL 2011	1.87	0.272
*"Proglacial lake terrace"	GBL 2013	6.48	0.812
			Mean 0.403
*Abandoned beach (south shore)	GBL 2003	1.52	0.182
*Abandoned beach (south shore)	GBL 2008	1.58	0.199
*Abandoned beach (south shore)	GBL 2010	1.38	0.140
*Abandoned beach (south shore)	GBL 2012	1.81	0.256
*Abandoned beach (south shore)	GBL 2014	1.69	0.228
			Mean 0.201
Present beach (south shore)	GBL 2005	1.54	0.188
Kame delta (present lake)	GBL 2023	3.87	0.588
Kame delta (present lake)	GBL 2024	1.97	0.294
Kame delta (present lake)	GBL 2025	1.52	0.182
			Mean 0.355

Samples marked * are paired; *i.e.*, beach sample taken directly above terrace sample at approximately 100-metre intervals from west to east.

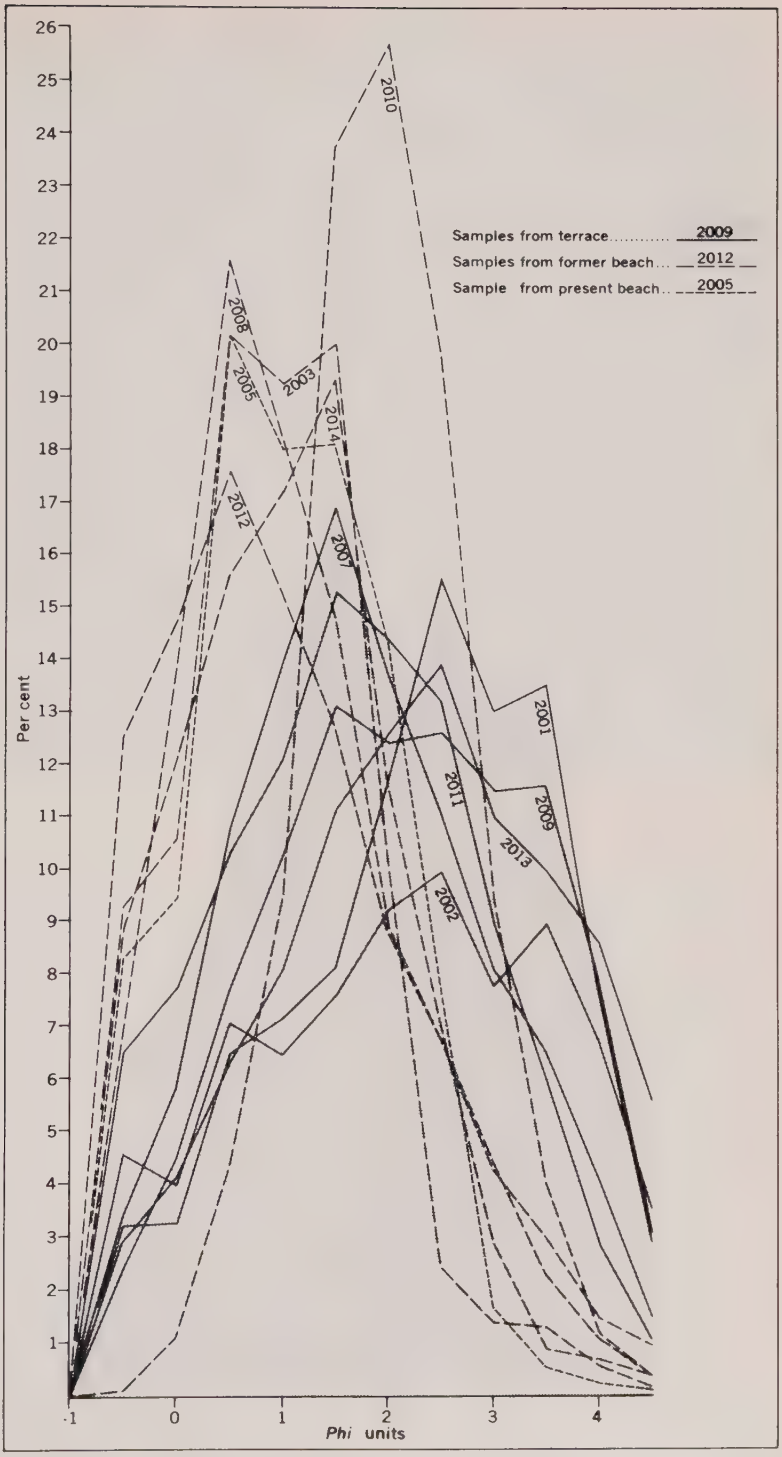


FIGURE 10
Grain sizes in *Phi* units showing contrast between beach and terrace samples. Particles finer than 44 microns have been omitted. The maximum omission occurs in No. 2013 where it amounts to 7.8 per cent of the sample.

FIGURE 11
Terrace sands overlying the till of the cross-valley moraine.

Landforms of the present lake

A similar series of landforms is associated with the present lake as with the former one. Particular investigation of submerged moraines by echo sounding will be continued and will be reported on separately.

A feature peculiar to the present lake is a "kame delta" that is forming between the proximal face of the lateral moraine and the ice at the south end of the ice cliffs. Variable sorting is apparent from three grain size analyses from this delta (Table 1), No investigation of possible sub-lacustrine prolongation of the delta into a terrace form has yet been undertaken.

Ice-pushed ridges occur around the edges of the present lake and Ward (1959, p. 437) observed and reported their mode of formation, though such vigorous genesis as he records is not an annual event.

Large sandy deltas are being built where streams enter the north side of the present lake.

THE AGE OF THE ABANDONED SHORELINE

Lichenometry as a dating technique

Beschel (1961) discussed the application of lichenometry to glaciology and physiography. Recently, Andrews and Webber (1964) assessed it as a geomorphological technique for the area northwest of the Barnes Ice Cap and found it a reliable relative dating method. More recently Jochimsen (1966) has questioned the validity of the technique and suggested that earlier Alpine correlations were fortuitous. On Baffin Island, Harrison (1966, p. 58) compared dating techniques in a small area and concluded that lichenometric discrepancies were probably microclimatic in origin. Nevertheless, lichenometry still appears to be the best available "absolute" dating method in the Arctic north of the tree line where sequential photography or material suitable for Carbon-14 dating is lacking. Although Reger and Péwé (*in* Péwé, *in press*) were able to use

dendrochronology in conjunction with lichenometry in central Alaska, stems of arctic willow (*Salix Arctica*) collected by the writer close to the Barnes Ice Cap rarely showed more than 20 growth rings.

The writer was one of the persons involved in sampling for Andrews and Webber and is therefore familiar with the general problems of the technique which, it is emphasized, should remain simple in order to be a practical geomorphological tool. Andrews and Webber dealt with the problems of a non-lichenologist confusing sub-species in the field but they concluded that measuring only the largest thalli would favour sampling the fastest growing sub-species (Andrews and Webber, 1964, p. 85).

The assumptions made in lichenometry are:

– that identification of species is correct and that sub-species with the fastest growth rate would occur most frequently in the ten largest measurements at any one site. In practice *Rhizocarpon geographicum sensu lato* is easily identified by its green and yellow colouration. In the present study, diameter measurements of this lichen were made from scanning about one thousand thalli of all sizes at each station.

– that the environment was lichen-free on exposure to sub-aerial conditions.

– that micro-environmental conditions are similar in any one area sampled. This means in practice that snow patch sites and moisture retaining hollows in rocks are avoided.

– that the diameter growth rate is linear for the time span being considered.

– that the largest thalli are the oldest and the optimally growing ones.

As a result of the distribution pattern of measurements taken in the present study the author has some reservations about the last assumption. Most of the measurements taken were of *R. geographicum s. l.* though some were of *Alectoria* and of *Buellia*. Figure 1 shows the largest and second largest diameters of *R. geographicum* at each of six sites, both above and below the shoreline. No sampling area was of a predetermined size but each was at least 10 metres away from the shore zone and did not extend laterally more than 20 metres either side of the starting point. This minor variation from Beschel's technique was used by Burrows and Lucas (1967, p. 467) "because of the irregularity of the terrain." It was also necessary to avoid snow-patch sites.

Examination of the diameter measurements of lichens from above the shoreline (Figure 12) reveals that three are significantly larger than the rest (60 recorded and about 6,000 scanned). None occur with diameters between 85 mm and 102 mm inclusive and yet a much greater uniformity of size is apparent if only the second largest diameters are considered. The hiatus of 18 mm (Figure 12a, I, II and IV) is large and would represent approximately 250 years without further successful colonization, assuming the revised growth rate calculated by Andrews (*in* Løken and Andrews, 1966, p. 359). Although the 250 year time span is within the calculated error term for the growth rate (Andrews, March, 1967, personal communication) the gap in the recorded measurements is real, though its causes are not known.

An attempt was made to estimate the probability that the three large lichens are part of the same population as the second largest at each of the three sites. Data from the 198 lichen samples used by Andrews and Webber (1964) were examined. Ratios of the second largest to the largest diameter of *R. geographicum* were calculated and are shown in Figure 13. The small ratios are the result of the measurements taken in the youngest environments where maximum diameters were only two or three millimetres. Despite this, the ratio lies within 10 per cent of the maximum in nearly 50 per cent of the samples and within 20 per cent in almost 75 per cent of the cases. Therefore, the probability of the three large lichens being from the same population can be considered low, though no more than a qualitative statement seems appropriate.

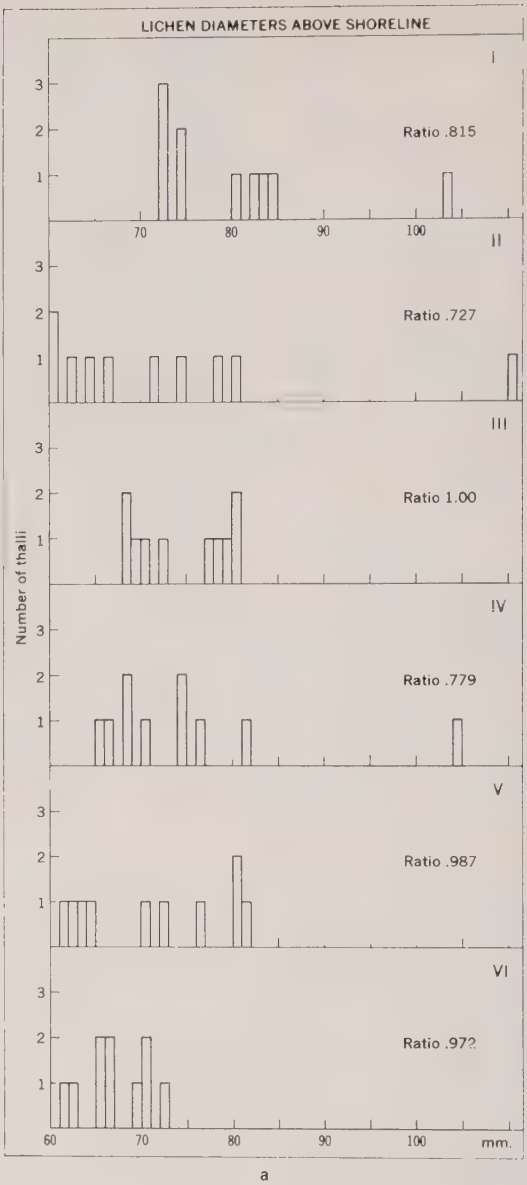
What then are the alternative explanations for the largest lichens? There are at least three possibilities. The first is that the microenvironment was peculiarly conducive to growth, for example, the thalli grew in a nutrient-rich location. The second is that the thalli were not in fact single but were compound with a quasicircular outline. Senescence above the 85 mm diameter thalli is a third possibility. In the case of the three thalli under consideration, they all appeared to be in good condition with

well-defined perimeters free from imminent coalescence and with no obvious decay at the centre. Assuming a thorough sampling of the area and, if one can, assuming a biological equivalence to the human population age pyramid, senescence is unlikely to be marked by so large a time gap near the peak. Beschel (1961, p. 1047) states that "the first thalli grow in a very scattered manner on a new rock surface with distributions of one plant to a few square meters" but even though such conditions could account for the few large ones they do not explain the gap to the next size range.

Although Sim (1961) took some measurements of *R. geographicum* from both above and below the Generator Lake shoreline it is impossible to assess these data accurately. Sim states that he measured the longest diameter where the thallus was elliptical in shape; this contrasts with the measurements of the shortest diameter in the present study.

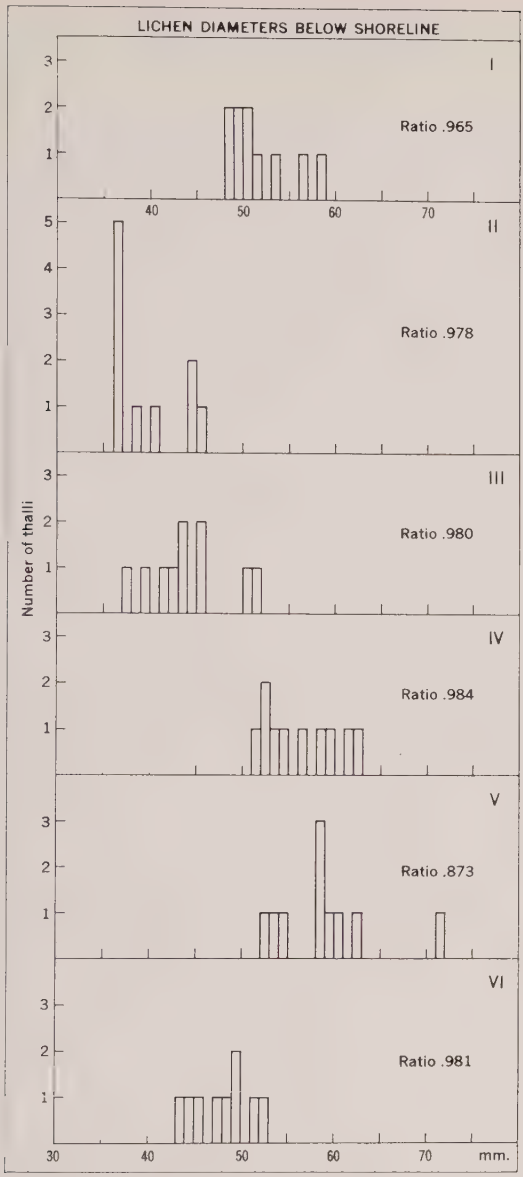
The acceptability of a single large lichen diameter measurement much larger than the next size group appears to be a potential problem of the technique, although it was used by Harrison (1964, p. 68) in estimating the age of a moraine in the Bruce Mountains, Baffin Island. The resolution of the problem probably lies with the lichenologist but it is important to recognize its existence at least, especially when approaching the maximum size of a species, as the whole technique is so dependent on the largest (oldest) thallus. The use of ratios of samples of different species can serve as a check though the duration of the uniform growth period is a potentially limiting factor in this respect.

Insufficient data are available to calculate an independent growth rate for *R. geographicum* for this area though useful data on the time necessary for initial establishment of the lichen was obtained. Several single spores up to 1 mm diameter were found in 1966 on the smooth surface of drill cores left by the 1950 Arctic Institute Expedition. An attempt to determine recent growth of an *Alectoria* thallus was partially successful. During the 1950 Arctic Institute Expedition, a photograph was taken which showed quite incidentally, a large *Alectoria* lichen but only incompletely. Fortunately it was in a recognizable position and was found and measured in August, 1965. It has grown visibly during the 15 years, though it is not possible to be precise as it was not measured in 1950. The expected increase in diameter would be 6 mm, using the Andrews and Webber (1964) growth rate of 0.4 mm per year – a rate more soundly based than the pioneer estimate by Hale (*see* Ward, 1952). This order of magnitude appears correct and



a

FIGURE 12. Ten largest lichen diameters of *Rhizocarpon geographicum sensu lato* from six paired stations located on Figure 1. Note ratios of second largest to largest.



b

obviously senescence has not yet set in at a diameter of 82 mm.

Provisional chronology

Allowing then for the reservations outlined above, a provisional chronology can be proposed for the lake from the findings of lichenometry. Thus far no material suitable for Carbon-14 dating has been found. Such a find would offer a check on the lichenometrical chronology, but only of an order of magnitude because of the inherent errors of each method.

By using the modified growth rate of 0.75 mm/year for *R. geographicum* as calculated for the northwest margin of the ice cap (Løken and Andrews, 1966, p. 359), an age and duration of the shoreline can be suggested.

As the present lichen measurements were confined to the western portion of the lake no specific allowance for the difference in time of sub-aerial exposure of the land above the shoreline has been included, as over the distance involved, the variation is probably within the error of the method.

If the large lichens are optimally growing then the lake existed approximately 1,470 years ago, though if the more uniform diameter measurements are used this decreases to 1,120 years. The difference in diameter of the lichens above and below the shoreline can be used to estimate the duration of the lake at its former level. The duration could be as long as 525 years (*R. geographicum* 71 mm) at a maximum, or 350 years if one ignores the largest lichens. When considering such time periods it should be remembered that the shoreline would be subject to water action for only a very small part of the year, perhaps only two months. Even these estimates give an order of magnitude and suggest stability for hundreds rather than tens of years.

Chronology and glacial rebound of the abandoned shoreline

It is believed that the area is still subject to glacial rebound, an assumption supported by the implications of the shape of uplift curves from both the east and west sides of Baffin Island (Løken, 1965; Andrews, 1966). Glacial Lake Lewis at the northwest margin of the Barnes Ice Cap, investigated by Ives (1962), drained approximately 400 years ago (revised date: Andrews *in* Løken and Andrews, 1966, p. 359). Ives (1962, p. 200) concluded that the shoreline was probably "so recent that no isostatic tilting has been able to affect it significantly." The age of the shoreline of Generator Lake was sufficiently greater than that of Lake Lewis to warrant levelling to detect any tilt. A line of levelling 22 km long was run along the more southerly shore of former Generator Lake but it failed to yield evidence for differential uplift. The end points (the extreme cairn

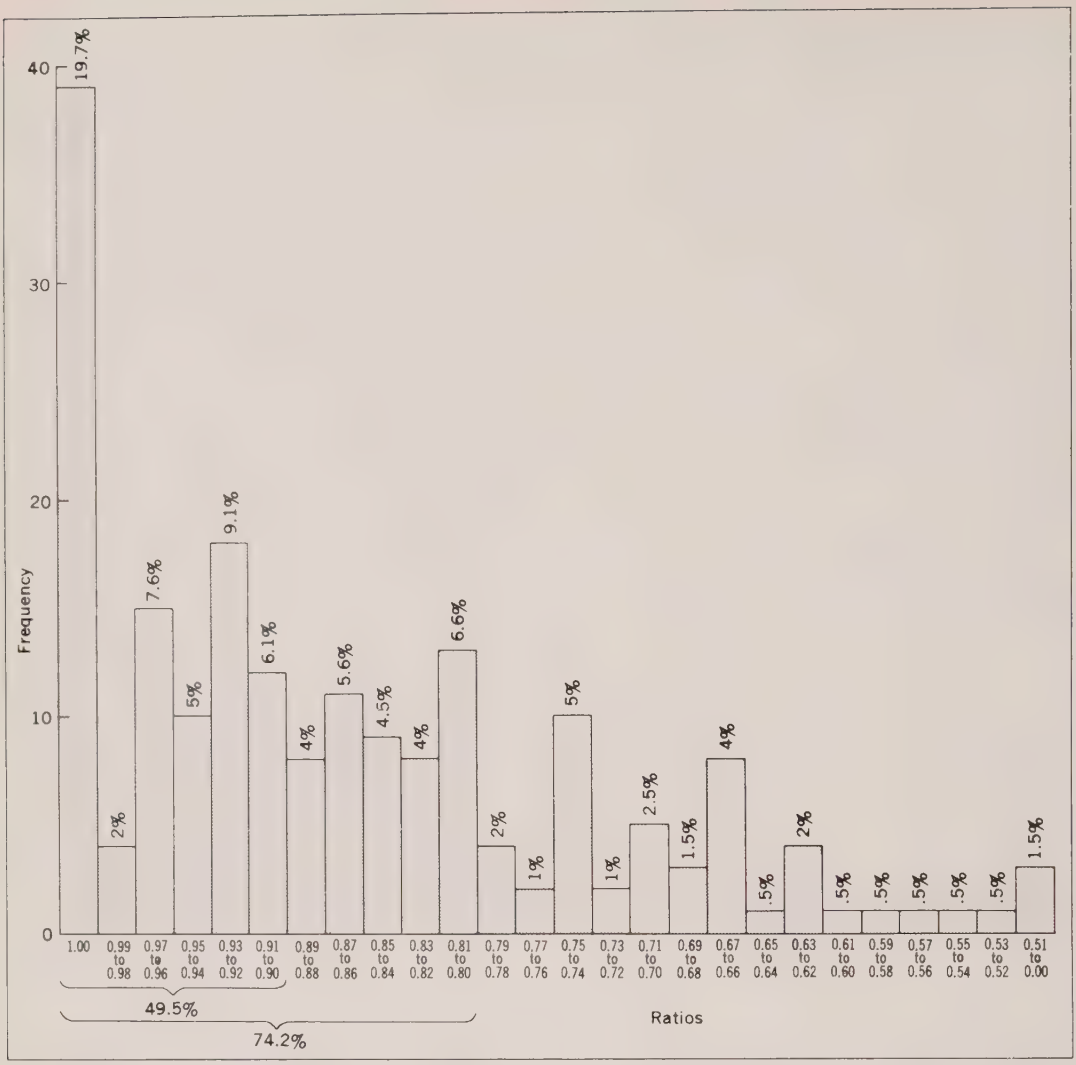


FIGURE 13. Ratios of second largest to largest *Rhizocarpon geographicum sensu lato* from 198 stations of Andrews and Webber's sampling (1964).

locations, Figure 1) had a difference in height of only 22.5 cm, well within the error of the method. The possibility of fortuitously following an isobase was avoided as the traverse has two components 65 degrees apart. Although it is concluded that the shoreline is essentially horizontal this does not preclude uplift but indicates that any which did occur was sufficiently uniform to be undetectable by levelling.

SUMMARY

During the 26-km retreat of the ice margin from the watershed, Generator Lake had two main phases in its evolution, tentatively estimated as lasting 1,500 years. The two bedrock controlled overflow channels were: first into the Sam Ford River and, currently, into the Clyde River.

Asymmetrical cross-valley moraines are the most striking landforms associated with the lake basin. Available stratigraphical evidence suggests that they have a sub-glacial origin, though further work is planned.

The present lake environment is similar to that of the former lake and a similar suite of landforms is present. This situation offers a

valuable opportunity for comparative study of landform development in a proglacial environment.

The period 1948-1966 was one of very active retreat of the ice cliffs, averaging 25 metres per year, with consequent equivalent increase in the area of Generator Lake.

Caution should be exercised in using chronology based on lichenometry near the upper size limit of a species. The recognition of the upper limit is difficult but critical if maximum benefit of this useful technique is to be gained.

A tentative chronology is: former lake fully established 1,500 to 1,100 years ago and draining to present level between 950 and 750 years ago. Draining was a rapid process.

The abandoned shoreline is not measurably deformed by glacial rebound.

ACKNOWLEDGMENTS

Thanks are extended to M. B. Foley, assistant in 1965 and G. T. Wagar assistant in 1966, together with a special expression of thanks to my senior assistant in both years, the late Bruce Bradley, and to David S. Harrison, pilot for Spartan Air Services, who carried out the precision flying for this project.

Appreciation is extended to Mrs. G. Mizerovsky who made the photogrammetric measurements as well as to several other members of the Department of Energy, Mines and Resources for their helpful discussion and comments during preparation of the manuscript.

REFERENCES

Andrews, J. T.
1963a: Cross-valley moraines of the Rimrock and Isortoq river valleys, Baffin Island, N.W.T. – a descriptive analysis. *Geog. Bull.*, no. 19, 49-77.

1963b: The cross-valley moraines of north-central Baffin Island: a quantitative analysis. *Geog. Bull.*, no. 20, 82-129.

1965 : Glacial geomorphological studies on north-central Baffin Island, N.W.T. Canada. Ph.D. thesis, Univ. Nottingham, 476 p. mimeo.

1966 : Pattern of coastal uplift and deglacierization, West Baffin Island, N.W.T. *Geog. Bull.*, v. 8, no. 2, 174-193.

Andrews, J. T. and Smithson, B. B.
1966 : Till fabrics of the cross-valley moraines of north-central Baffin Island, Northwest Territories, Canada. *Geol. Soc. Am. Bull.*, v. 77, 271-290.

Andrews, J. T. and Webber, P. J.
1964 : Lichenometric study of the northwestern margin of the Barnes Ice Cap: a geomorphological technique. *Geog. Bull.*, no. 22, 80-104.

Baird, P. D., *et al.*
1950 : Baffin Island Expedition: a preliminary report. *Arctic*, v. 3, no. 3, 131-149.

Beschel, R. E.
1961 : Dating rock surfaces by lichen growth and its application to glaciology and physiography (lichenometry). Raasch, G. O. (ed.), *Geology of the Arctic*, v. 2, 1044-1062, Univ. Toronto Press, Toronto.

Bird, J. B.
1967 : *The Physiography of Arctic Canada*, Johns Hopkins, Maryland, 336 p.

Burrows, C. J. and Lucas, J.
1967 : Variations in two New Zealand glaciers during the past 800 years. *Nature*, v. 216, no. 5114, 467-468.

Charlesworth, J. K.
1957 : *The Quaternary Era*. Edward Arnold, London, 2 vols., 1700 p.

Department of Transport
1965 : Monthly Record (July-August), Meteorological Service, Toronto.
1966 : Monthly Record (July-August), Meteorological Service, Toronto.

Friedman, G. M.
1962 : On sorting, sorting coefficients, and the lognormality of the grain-size distribution of sandstones. *J. Geol.*, v. 70, no. 6, 737-753.

Goldthwait, R. P.
1951 : Development of end moraines in east central Baffin Island. *J. Geol.*, v. 59, 567-577.

Hale, M. E.
See reference to Ward, 1952.

Harrison, D. A.
1964 : A reconnaissance glacier and geomorphological survey of the Duart Lake area, Bruce Mountains, N.W.T. *Geog. Bull.*, no. 22, 57-71.
1966 : Recent fluctuations of the snout of a glacier at McBeth Fiord, Baffin Island, N.W.T. *Geog. Bull.*, v. 8, no. 1, 48-58.

Ives, J. D.
1962 : Indications of recent extensive glacierization in north-central Baffin Island, N.W.T. *J. Glaciol.*, v. 4, no. 32, 197-205.

Jochimsen, M.
1966 : Ist die Grösse des Flechtenthallus wirklich ein brauchbarer Masstab zur Datierung von glazialmorphologischen Relikten. *Geog. Annaler*, v. 48A, no. 3, 157-164.

Krumbein, W. C. and Pettijohn, F. J.
1938 : *Manual of Sedimentary Petrography*. Appleton Century Crofts, New York, 549 p.

Littlewood, C. A.
1952 : Gravity measurements on the Barnes Ice Cap, Baffin Island. *Arctic*, v. 5, no. 2, 118-124.

Løken, O. H.
1965 : Postglacial emergence at the south end of Inugsuin Fiord, Baffin Island, N.W.T. *Geog. Bull.*, v. 7, 3-4, 243-258.

Løken, O. H. and Andrews, J. T.
1966 : Glaciology and chronology of fluctuations of the ice margin at the south end of the Barnes Ice Cap, Baffin Island, N.W.T. *Geog. Bull.*, v. 8, no. 4, 341-359.

Nichols, Robert L.
1952 : Marine and lacustrine ice-pushed ridges. *J. Glaciol.*, v. 2, no. 13, 172.

Price, R. J.
1965 : The changing proglacial environment of the Casement Glacier, Glacier Bay, Alaska. *Inst. Brit. Geog. Trans. and Papers*, no. 36, 107-116.

Rand Corporation
1963 : A report on the physiographic conditions of central Baffin Island and adjacent areas, N.W.T. Canada. Memorandum R.M. – 2837-1-PR, 270 p. USAF Project Rand.

Reger, R. D. and Péwé, T. L.
1968 : Lichenometric dating in the central Alaska Range: *in* Péwé, T. L. *The periglacial environment* (*in press*).

Sim, V. W.
1961 : 1961 field notes: Home Bay Map Sheet, Baffin Island, N.W.T., Geog. Br., 44 p. mimeo., (unpub.).

Smithson, B. B.
1965 : The glacial geomorphology of the Upper Isortoq River, Baffin Island, N.W.T. Unpub. M.Sc. thesis presented to Univ. Western Ontario.

Ward, W. H.
1952 : The physics of deglaciation in central Baffin Island (with appendix by M. E. Hale). *J. Glaciol.*, v. 2, no. 11, 9-23.
1959 : Ice action on shores. *J. Glaciol.*, v. 3, p. 437.

Weertman, J.
1961 : Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets. *J. Glaciol.*, v. 3, 965-978.

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 189–217, 1967

LES PINGOS DE L'ILE PRINCE-PATRICK (76°N – 120°W)

*A. Pissart**

RÉSUMÉ

Plus de 150 pingos ont été observés sur l'île Prince-Patrick. La majorité de ces buttes de glace d'injection se groupent en deux ensembles distincts:

Le premier comprend plus de 100 pingos situés sur la surface sommitale de l'île à une altitude voisine de 100 m. Ces formes s'alignent en deux rangées parallèles et se présentent généralement sous forme de buttes circulaires en plan, dont la hauteur et le diamètre n'excèdent pas respectivement 13 m et 250 m. Ne présentant aucune trace certaine d'évolution actuelle et ne montrant aucune relation avec la topographie, ces formes existent aussi bien dans les vallées que sur les sommets. Il est vraisemblable qu'elles sont en relation avec une structure géologique profonde.

Le second groupe de pingos est constitué de buttes qui sont situées à une altitude proche du niveau de la mer, au fond de deux baies éloignées l'une de l'autre de plus de 90 km. A côté de formes circulaires caractéristiques, appartiennent surtout à ce groupe des pingos allongés semblables à des eskers. Des coupes observées ont montré la disposition des couches dans le flanc des pingos et aussi le noyau de glace d'injection. Ils paraissent nés à la suite d'un mouvement positif du niveau de la mer ayant ennoyé la baie et causé la fusion de la partie supérieure du permafrost. Le rétablissement ultérieur du permafrost aurait été à l'origine de l'apparition de cette glace d'injection.

Quelques autres pingos, d'un type différent, ont été reconnus sur l'île.

ABSTRACT

More than 150 pingos have been observed on Prince Patrick Island. The majority of these domes of injected ice may be divided into two distinct groups:

The first group is made up of more than 100 pingos located on the surface of the island's summit at an altitude of about 100 metres. They are aligned in two parallel rows of domes, circular in ground plan, whose height and diameter do not exceed 13 metres and 250 metres respectively. Presenting no positive trace of present day evolution and showing no relationship with the topography, these forms exist in the valleys as well as on the summits. They are possibly related to some deep geological structure.

The second group of pingos is made up of domes at an altitude close to sea level and situated at the head of two bays more than 90 km distant from each other. In this group particularly are elongated pingos resembling eskers as well as those with the characteristic circular shape. Observed cuts have shown the arrangement of layers in the sides of the pingos as well as the core of injected ice. They appear to have developed following a definite change of sea level which drowned the bay and resulted in the melting of the upper permafrost. The later re-establishment of the permafrost may have begun with the appearance of this injected ice.

Other pingos of a different type have also been recognized on the island.

MS submitted May, 1966

*M. Albert Pissart est Chargé de Cours Associé au Laboratoire de géologie et de géographie physique de l'Université de Liège, dont le Professeur Paul Macar est le Directeur. Pendant ses recherches dans l'Arctique, M. A. Pissart était employé par la Direction de la géographie à titre temporaire.

INTRODUCTION

Au cours de la dernière décennie, les recherches portant sur les pingos se sont multipliées. Nous rappellerons notamment les publications de F. Müller (1959), de J. Ross Mackay (1962), de G. W. Holmes, D. M. Hopkins et H. L. Foster (1963), et de G. C. Maarleveld.

De ces travaux, il résulte principalement que deux types de pingos, génétiquement différents, ont été reconnus dans l'Arctique. Cette distinction, déjà proposée par Porsild en 1938, paraît être aujourd'hui largement admise.

Le premier type de pingo est bien représenté dans le delta du Mackenzie. Il est constitué par des formes localisées dans des lacs peu profonds ou actuellement asséchés, et leur genèse est liée à cette position particulière. En effet, sous les lacs de l'Arctique dont la profondeur dépasse l'épaisseur de la glace d'hiver, le sous-sol n'est pas gelé et cela, même si dans la région existe un permafrost continu et profond. Si, à la suite d'un remblaiement ou d'une baisse de niveau lacustre, l'épaisseur de la lame d'eau diminue, le contenu du lac est en hiver entièrement transformé en glace, et le fond du lac lui-même commence à geler. De la sorte, le permafrost voisin progresse et vient conquérir la zone située sous le lac. Cette progression détermine l'encerclement d'une poche de sédiments gorgés d'eau et non gelés, par un sol gelé imperméable. L'augmentation de volume consécutive à la transformation en glace de l'eau de cette enceinte engendre une pression élevée qui injecte de l'eau profonde dans les couches supérieures où elle vient former le noyau de glace d'un pingo en croissance.

Ce mécanisme exige la présence d'un sol gelé profond et permanent qui correspond à un climat très rigoureux. La température moyenne annuelle des régions nord américaines où existe ce type de pingo varie selon Holmes, Hopkins et Foster, entre 12° et 22°F (–11° et –5°5 C).

Le second type de pingo apparaît dans des régions présentant un relief bien marqué. Des pentes sont en effet indispensables pour déterminer leur apparition. Ici, la pression nécessaire à l'injection n'est plus engendrée par le gel lui-même, mais par une circulation d'eau souterraine se produisant sous une couche gelée et alimentée par de l'eau superficielle descendant du versant. L'injection d'eau dans les couches supérieures gelées s'effectue en des endroits situés en contrebas et où la couche supérieure gelée est moins résistante.

Les conditions climatiques nécessaires à l'apparition de ce type de formes sont bien moins rigoureuses que les précédentes. Les auteurs déjà cités mentionnent pour les pingos de l'intérieur de l'Alaska des températures moyennes annuelles de l'air variant entre 22° et 28°F (–5°5 et –2°2 C). Des pingos du même type ont cependant été décrits au Groenland par F. Müller dans des conditions plus rigoureuses, la température moyenne annuelle y atteignant parfois –10° C.

Nous avons montré dans un article récent (Pissart, 1965) que des traces de pingos existent en Belgique dans une situation topographique qui exclut les deux hypothèses génétiques décrites précédemment. Ces traces de pingos ont en effet été trouvées au sommet d'une crête relativement étroite où les mécanismes vus plus haut n'ont pu se produire.

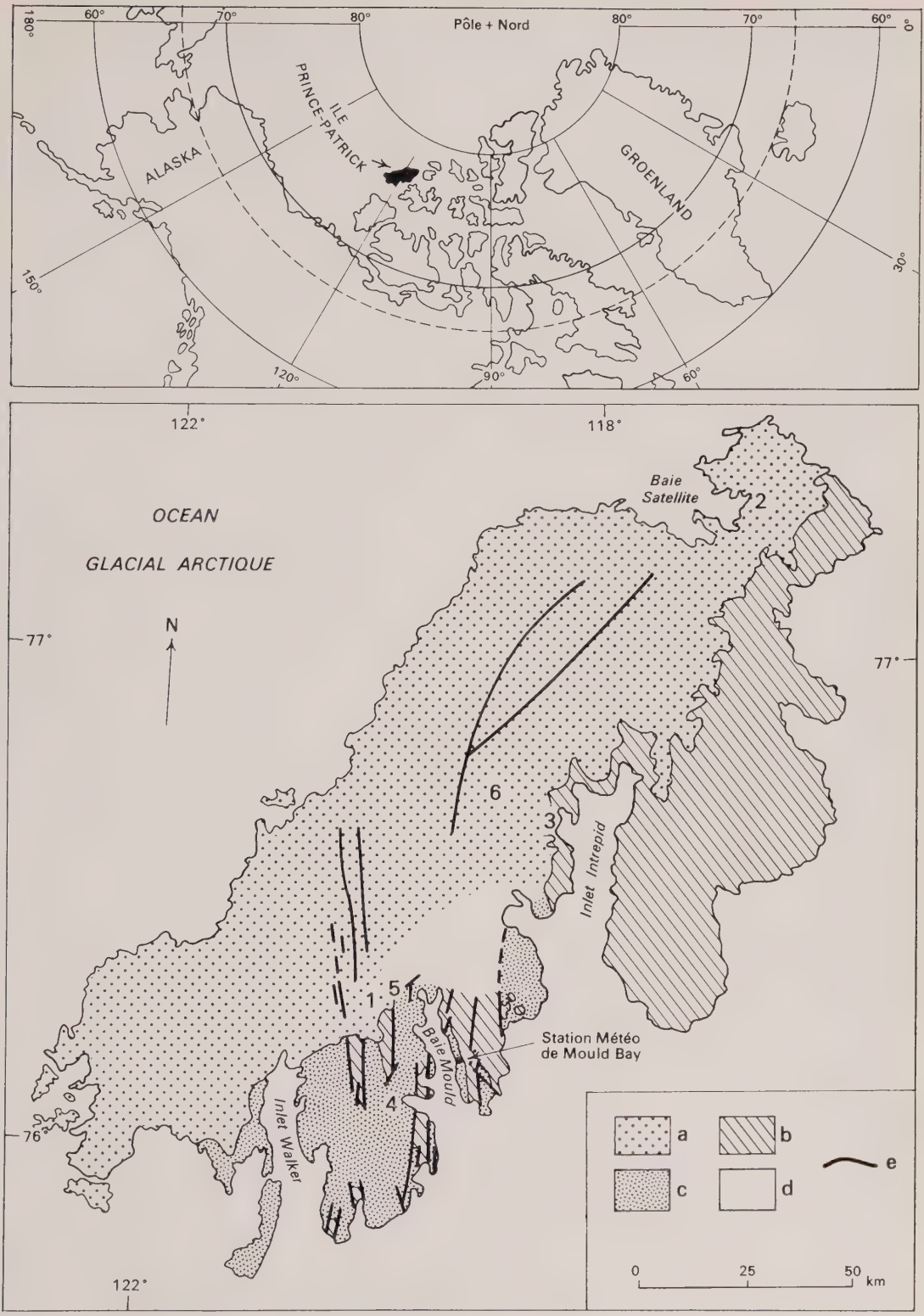
Plusieurs auteurs pensaient d'ailleurs avant nous que d'autres types de pingos existaient, puisque J. Ross Mackay (1962, p. 22) et F. Müller (1959) ont signalé quelques pingos qui n'appartiennent à aucune des deux catégories décrites plus haut. Les pingos de l'île Prince-Patrick, que nous allons présenter, sont également des formes d'une catégorie distincte et, à ce titre, ils méritent une attention spéciale.

GEOLOGIE, HISTOIRE GEOMORPHOLOGIQUE RECENTE ET CLIMAT DE L'ILE PRINCE-PATRICK

L'île Prince-Patrick fait partie des îles Reine-Elisabeth et s'étend principalement entre le 76e et le 77e parallèle, de part et d'autre du 120e méridien de longitude ouest (Figure 1).

Située au bord de l'Océan glacial arctique, les deux tiers de sa surface se présentent comme une plaine maritime typique, en pente douce vers l'ouest et drainée par un réseau

FIGURE 1
Grands traits de la géologie de l'île Prince-Patrick, d'après Tozer et Thorsteinsson (1964, Figure 12).
a. Formation de Beaufort (Tertiaire ou Pléistocène).
b. Pennsylvanien, Permien, Mésozoïque et Tertiaire.
c. Ordevicien, Silurien et Dévonien.
d. Inconnu.
e. Failles.
1 à 6: emplacements des pingos étudiés.


Pôle + Nord
ALASKA
ILE PRINCE-PATRICK
GROENLAND
OCEAN GLACIAL ARCTIQUE
N
Baie Satellite
Inlet Intrepid
Baie Mould
Station Météo de Mould Bay
Inlet Walker
a
b
c
d
e
0 25 50 km

dendritique caractéristique. Le substratum de cette région est constitué de couches subhorizontales de sables et de graviers reposant en discordance de stratification sur les formations secondaires et primaires qui affleurent à l'est de l'île. C'est sur cette formation sablo-graveleuse, appelée formation de Beaufort que se localise la majorité des pingos que nous avons étudiés. Bien que de très nombreux débris de bois y soient conservés, l'âge de cette formation de Beaufort n'est pas connu. Les auteurs qui l'ont étudiée (Tozer et Thorsteinsson, 1964, p. 167) ont établi qu'il s'agissait d'un dépôt datant du Tertiaire ou du début du Quaternaire. A en juger par l'importance de l'érosion postérieure à la mise en place de ces sédiments, nous pensons qu'il s'agit plutôt d'une assise d'âge tertiaire.

Les formations inférieures dont l'âge est tantôt dévonien et tantôt secondaire sont généralement peu inclinées. Toutefois, des failles radiales les découpent (Figure 1) et, comme Tozer et Thorsteinsson (1964, p. 20) l'ont observé, certains de ces accidents paraissent affecter la formation de Beaufort. En effet, ces auteurs ont remarqué sur photos aériennes, l'existence de lignes droites ou légèrement arquées, longues de plus de 50 km qui n'apparaissent pas dans la topographie, mais séparent des régions présentant une végétation légèrement différente. Le fait qu'elles prolongent parfois des failles reconnues dans les formations inférieures, explique que Tozer et Thorsteinsson y voient la prolongation des mêmes failles radiales.

L'histoire géomorphologique de la région n'est pas bien connue. Une grande glaciation au moins a recouvert toute l'île ainsi qu'en témoignent de nombreux erratiques. A part quelques très rares roches striées et des traces de nombreux chenaux d'écoulement d'eau de fonte glaciaire, les restes de la glaciation sont très peu apparents. L'érosion postérieure semble montrer qu'il s'agit d'une glaciation ancienne. Fyles (1965, p. 4) exprime la même opinion lorsqu'il écrit que la distribution des erratiques dans la partie est de l'île suggère que la grande glaciation qui les a amenés est antérieure à la dernière période froide.

Au Wisconsin, l'île ne paraît pas avoir subi une glaciation importante. Il est toutefois probable qu'une calotte glaciaire locale peu épaisse l'ait recouverte sans cependant laisser de traces nettes dans la topographie.

La géomorphologie de l'île Prince-Patrick est donc en grande partie périglaciaire. Le permafrost y est certainement très profond mais aucun sondage n'a été réalisé à ce jour et son extension n'est donc pas connue. Rappelons cependant qu'à 300 km au sud-est, sur l'île Melville, un sondage profond a montré que le sol était gelé jusqu'à une profondeur de 515 m (Hamelin et Jacobsen, 1964, p. 15). Sur photos aériennes, quelques indices d'existence de plages soulevées semblent apparaître. Sur le terrain cependant, aucun coquillage n'a pu être trouvé, les formes d'érosion marine sont peu nettes et, à ce sujet également, les connaissances sont réduites.

Le climat actuel de l'île Prince-Patrick est extrêmement rigoureux. Des observations météorologiques faites à Mould Bay depuis 1948, il résulte que la température moyenne annuelle est de −18°5 C (−1°5 F). Le tableau des températures moyennes mensuelles donné en appendice montre que la moyenne mensuelle ne dépasse 0°C, que pendant juillet et août, et que le gel est intense pendant neuf mois par an. La faiblesse des précipitations (moyenne annuelle 81 mm = 3.23 inches) permet de comprendre qu'une calotte glaciaire ne recouvre pas toute l'île de nos jours.

Le tableau des moyennes mensuelles qui rassemble des indications climatiques comparables pour l'île Prince-Patrick et des régions du Groenland et du delta du Mackenzie où ont été observés des pingos, permet de se rendre compte que le climat de la région étudiée ici est beaucoup plus rigoureux.

LES PINGOS, DESCRIPTION ET HYPOTHESES GENETIQUES

L'étude systématique des photos aériennes de l'île Prince-Patrick a révélé l'existence en plusieurs endroits de l'île, de buttes isolées, plus ou moins circulaires qui paraissent à première vue être des pingos. Souvent il a été impossible de décider s'il s'agissait réellement de buttes dues à l'apparition de noyaux de glace d'injection ou s'il s'agissait de simples collines dégagées par le hasard de l'érosion. Nous ne nous attarderons pas à la description des formes hypothétiques et nous décrirons seulement les

pingos indiscutables. La majorité de ceux-ci peuvent être groupés en deux ensembles totalement différents, au point de vue genèse et âge, comme en ce qui concerne leur localisation. Pour ces raisons nous les considérons séparément. Le premier de ces groupes de pingos est localisé à 18 milles (29 km) au nord-ouest de Mould Bay, au sommet de l'île (point 1 de la Figure 1), tandis que le second rassemble des formes apparues au bord de la mer et que nous avons observées près de la baie Satellite et de l'inlet Intrepid (points 2 et 3 de la Figure 1).

LES PINGOS LOCALISES AU SOMMET DE L'ILE, AU NORD-OUEST DE MOULD BAY

Ces pingos ont été reconnus pour la première fois pendant l'été 1964 par J. G. Fyles, chef de la section de la géologie du Pléistocène, ministère de l'Energie, des Mines et des Ressources. Il nous avait autorisé très aimablement à étudier ces formes et a eu la bienveillance de nous communiquer avant notre départ sur le terrain, les photos qu'il en avait prises. Nous l'en remercions très vivement.

Description du relief

Le plateau où se localisent les pingos observés s'étale à 18 milles (29 km) au nord-ouest de la station météorologique de Mould Bay. Il fait partie de la surface sommitale de l'île et les rivières qui y prennent leur source divergent; les unes s'écoulent vers l'ouest en direction de l'Océan glacial arctique, d'autres se dirigent vers le sud-ouest en direction de l'inlet Walker et d'autres encore, s'en vont rejoindre la mer au sud-est, dans la baie Mould.

Ce plateau dont l'altitude est d'environ 100 m est découpé par des vallées peu profondes mais très larges. Celles-ci offrent quelques particularités remarquables; souvent elles se continuent d'un bassin à l'autre sans qu'il existe de véritable tête de vallée. De ce fait, il est absolument impossible de tracer sur les photos aériennes la limite des différents bassins. Elles sont en outre disproportionnées, beaucoup trop larges pour les cours d'eau qui les empruntent aujourd'hui; enfin, elles se recoupent parfois perpendiculairement. Au total, elles sont inexplicables par la simple érosion normale et on ne peut les comprendre que comme des chenaux d'écoulement glaciaire. Ces chenaux sont, avec quelques erratiques parfois volumineux, les traces les plus apparentes d'une glaciation dont l'ancienneté est attestée par le fait que les formes fluviatiles sont estompées par la solifluxion. Fyles (1965, p. 4) a également observé sur l'île Prince-Patrick une topographie dont l'origine morainique est possible: des collines ressemblant à des kames, et deux rides de graviers qui semblent être des eskers.

De nombreux étangs jalonnent les parties supérieures des vallées. Certains sont dus à la solifluxion qui apporte dans le fond des vallées de nombreux cailloux dont la taille dépasse la compétence des cours d'eau; n'étant pas emportés par l'eau courante, ils s'accumulent et finissent par engendrer des contre-pentes locales. D'autres proviennent de l'obturation des vallées par des pingos et d'autres encore, temporaires cette fois, sont occasionnés par des bancs de neige. Lorsque l'écoulement d'un petit lac dû à l'obturation de la vallée par un banc de neige se fait par une autre issue que le banc de neige lui-même, celui-ci n'est pas incisé par l'eau de fonte et si la neige persiste, ce petit lac subsiste sans doute plusieurs années.

Ajoutons, pour terminer cette description, que ce plateau est modelé dans les sables et graviers de la formation de Beaufort. Souvent, un certain pourcentage de sédiments plus fins est présent dans ces sables et c'est cette fraction fine qui permet le développement des phénomènes de solifluxion dont nous venons de parler.

La Figure 2 dessinée d'après photos aériennes montre la répartition des pingos que nous avons reconnus dans cette région. Elle permet d'observer que ces buttes sont très nombreuses, plus de 130, et qu'elles se groupent en deux alignements ouest sud-ouest — est nord-est, longs de plus de 15 km. Ces alignements très nets, séparés par une zone large de plus de 2 km sans aucun pingo, ne sont nullement en relation avec la topographie. Ils s'étendent selon la direction qui leur est propre sans tenir compte des formes du relief et les pingos qui les constituent sont localisés indifféremment sur les sommets, dans les fonds des vallées, et sur les versants.

En 1965, nous avons parcouru cette région durant sept jours avec W. S. B. Patterson, de

FIGURE 2. Pingos reconnus sur la surface sommitale de l'île Prince-Patrick, 18 milles (29 km) au nord-ouest de Mould Bay. Noter leurs alignements—Carte dessinée d'après des photos aériennes.

FIGURE 3. Pingo caractéristique, loupe circulaire peu élevée (2 m) au-dessus du plateau et apparaissant clairement au début de juin 1965 parce qu'elle a été dégagée de toute neige par la déflation éolienne.

l'Etude du plateau continental polaire, qui nous a aidés considérablement à effectuer ces mesures et qui a recherché longuement avec nous l'origine de ces formes. Le diamètre moyen des 70 pingos que nous avons mesurés sur le terrain est de 59 m, leur hauteur moyenne est de 3.30 m. Il s'agit donc généralement de formes de faible dimension: les plus petites buttes étudiées ont seulement un mètre de haut et 20 m de diamètre, la plus grande atteint 250 m de diamètre et 13 m de hauteur.

Généralement, ces buttes ont une forme en plan à peu près circulaire (Figure 3); les quelques pingos dont le pourtour dessine un tracé nettement différent sont dus à l'accolement de plusieurs buttes circulaires reconnaissables.

Les formes les plus petites ont le plus souvent un aspect de loupe, de coupole aplatie (Figure 4a). Quelquefois, au sommet de cette coupole existe un sommet plus aigu (Figure 4b). Un aspect en tronc de cône est fréquent pour les formes moyennes (Figures 4c et 4d). Quant aux buttes les plus grandes, elles présentent très généralement un aspect mamelonné irrégulier (Figures 5 et 6), car elles sont parsemées de sommets dont la disposition, vue sur des profils, semble montrer l'existence d'un cratère central (Figures 4e et 4f). Enfin, des buttes nées de la juxtaposition de deux, trois ou quatre formes circulaires bien individualisées ont une forme très variable en fonction de la disposition des unités qui les constituent (Figure 4g).

Sur le terrain, ces différents types de pingos ne sont généralement pas dispersés sans ordre. Au contraire, ils sont le plus souvent groupés par catégories, qu'il s'agisse des formes les plus simples ou les plus complexes.

De nombreux pingos ont été examinés attentivement en vue de rechercher des traces d'évolution actuelle. Ils sont toujours recouverts de sables et de graviers. Les cailloux forment le plus souvent en surface une espèce de dallage qui, toutefois, ne masque pas totalement les sables sous-jacents. Les cailloux situés sur ces buttes sont souvent recouverts de lichens noirs, indice d'une certaine ancienneté et d'une certaine stabilité. Les éléments présentant un poli éolien sont assez rares, les cailloux à facettes éoliennes sont tout à fait absents. Ceci représente un fait général sur l'île Prince-Patrick, même là où les sables sont abondants. L'éolisation paraît faible parce que les vents violents sont très peu fréquents. (Pissart, 1966).

De légères dépressions ayant la forme des rigoles profondes de 10 à 20 cm dessinent sur ces pingos un réseau de polygones dont le diamètre atteint souvent 20 m. Les cailloux y sont plus nombreux, entassés les uns sur les autres comme si le sable qui les accompagnait avait disparu en profondeur. Parfois, des polygones plus petits de 5 m de diamètre, sont

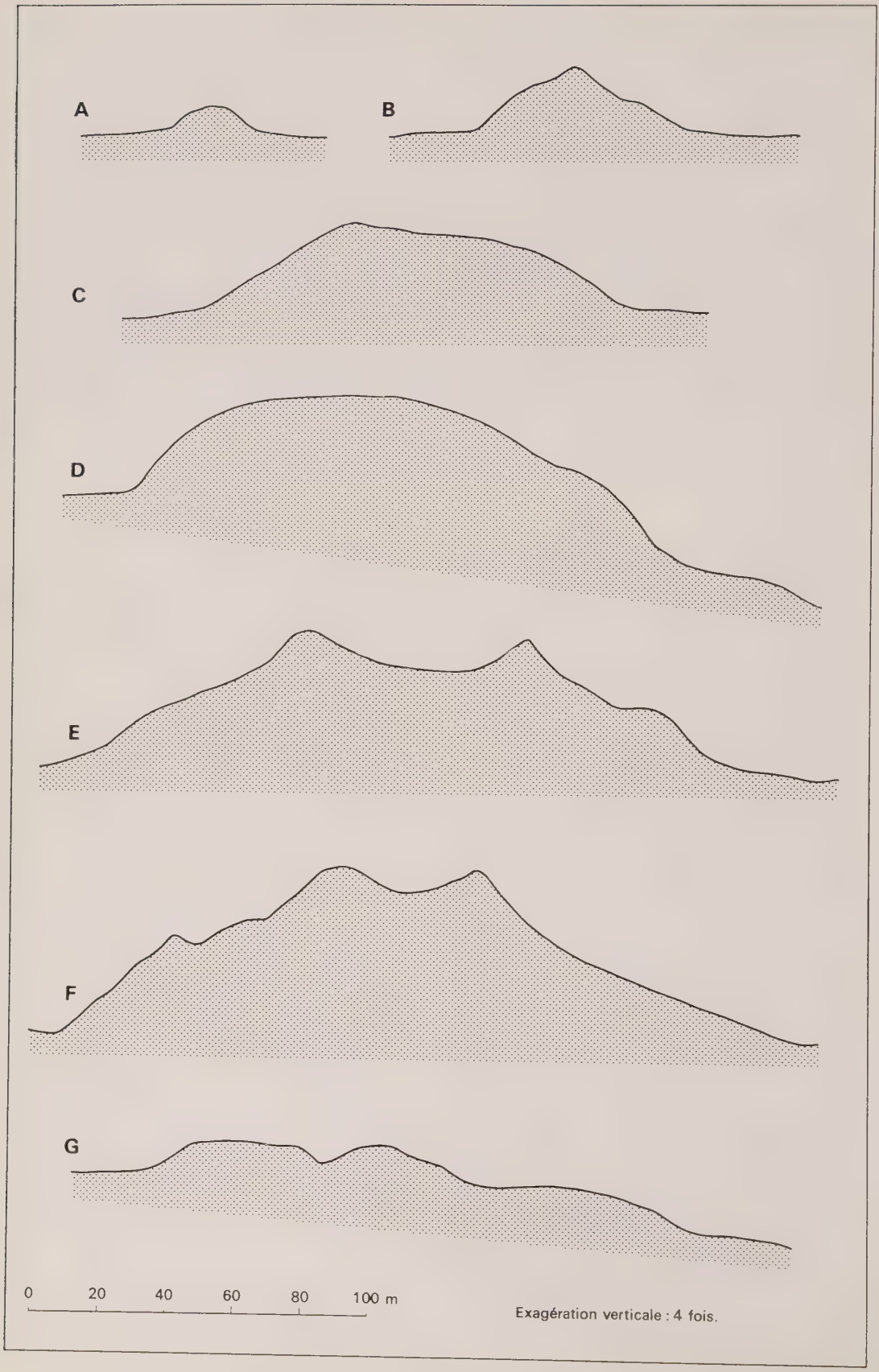

A
B
C
D
E
F
G
0
20
40
60
80
100 m
Exagération verticale : 4 fois.

FIGURE 4
Profils des différents types de pingos reconnus au sommet de l'île à 18 milles (29 km) au nord-ouest de Mould Bay. Ces profils ont été levés sur le terrain à l'aide d'un niveau d'abney et d'un mètre ruban.

emboîtés dans les précédents et pour ceux-ci les fissures qui les limitent sont moins profondes, moins marquées. La persistance de ces accidents sur des pentes fortes atteignait parfois 20 degrés, l'absence de lichens sur les bords de ces polygones où une certaine descente vers le milieu des fissures semble se produire, montrent que ces structures évoluent de nos jours. Nous verrons plus loin, en décrivant les coupes observées, qu'il s'agit de polygones de fente de gel tantôt à remplissage de glace et tantôt à remplissage uniquement minéral.

Comme nous l'avons vu plus haut, la forme des plus grands pingos est souvent irrégulière, car des sommets relativement aigus leur donnent une allure mamelonnée. Souvent ces formes sont associées à de petites dépressions de 1 à 3 m de diamètre et atteignant 50 cm de profondeur. Nous croyons que cet ensemble de faits est le résultat d'un début de fusion d'une masse de glace sous-jacente, noyau central du pingo. Si cette interprétation paraît évidente pour les dépressions fermées, elle demande cependant d'être étayée en ce qui concerne les sommets aigus. Trois arguments peuvent être avancés en faveur de cette façon de voir:

(a) Comme nous venons de le dire, ces sommets secondaires sont associés aux dépressions fermées.

(b) Des buttes identiques ont été observées près de la baie Satellite sur des pingos indiscutablement en fusion (*voir* Figure 12).

FIGURE 5
Grand pingo en fusion situé au sommet de l'île à 15 milles au nord-ouest de Mould Bay:

Hauteur maximum: 11 m.
Diamètre: 210 m.

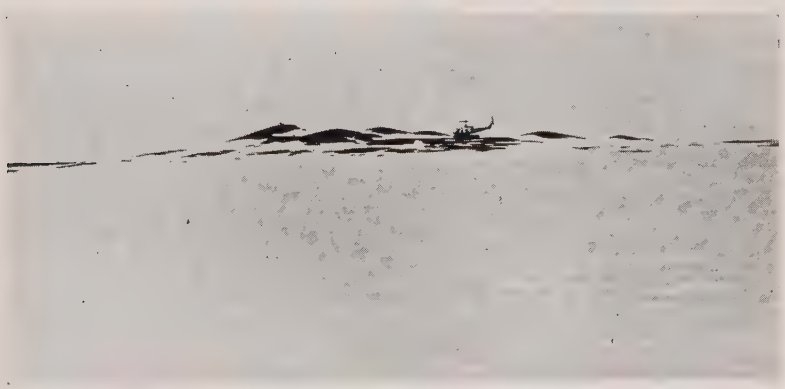


FIGURE 6
Même pingo, vue aérienne.

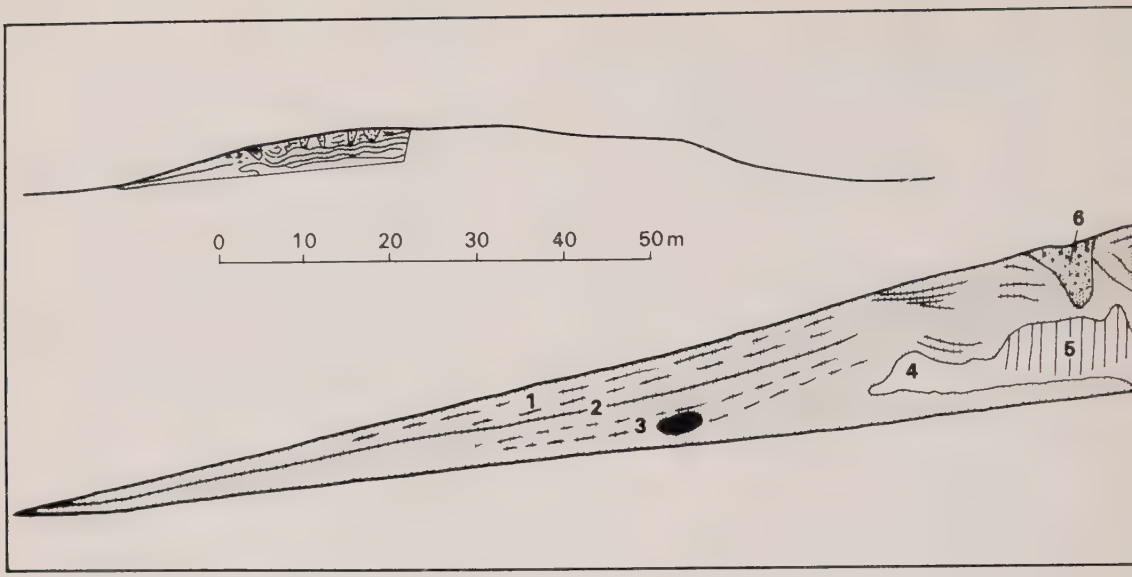


FIGURE 7. Coupe dégagée dans le pingo note II, sur la Figure 2.

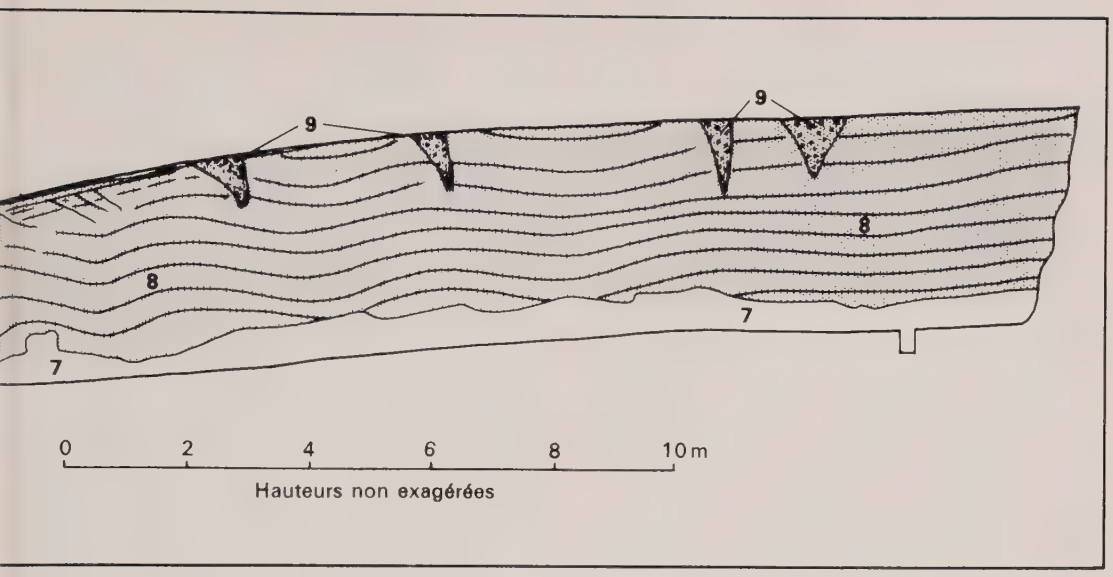
1. Sables et petits graviers présentant un litage mal défini: dépôts de pente.
2. Contact peu net avec des sables et graviers plus grossiers.
3. Bloc de pierre de 0,7 x 0, 5 x 0,3 m—erratique probable.
4. Glace d'injection probablement. Longueur des plus gros cristaux: 2 cm.
5. Glace de fente en coin, stratifiée verticalement.
6. Coin correspondant, dans la couche active, au coin de glace sous-jacent.
7. Glace d'injection. Dimension des cristaux: 0,2 à 1 cm.
8. Couches de sables et de graviers bien stratifiées et légèrement ondulées: formation de Beaufort probablement en place.
9. Structures de polygones de gel à remplissage minéral.

(c) Les quelques coupes que nous avons dégagées paraissent montrer que si une stratification régulière et parallèle à la surface s'observe sur le versant extérieur du pingo, celle-ci est souvent dérangée à l'emplacement des irrégularités qui existent en son centre, comme s'il s'agissait du résultat d'un affaissement de cette partie.

Les pentes de ces pingos sont généralement inférieures à 20 degrés et sont donc toujours nettement inférieures à la valeur de l'éboulis de gravité. L'inclinaison est la plus forte là où des bancs de neige subsistent tardivement, et c'est visiblement la conséquence de la nivation.

En conclusion, l'aspect des versants de ces pingos ne diffère pas de l'aspect des pentes des vallées voisines: les mêmes polygones de tundra y existent et ces pentes ont généralement une inclinaison inférieure à 20 degrés. Les pentes plus raides sont le résultat de l'action de la nivation. La fusion dont on observe les traces ne paraît pas se produire de nos jours, ou elle est, à tout le moins, si lente qu'elle n'est pas apparente extérieurement. En bref, nos observations ne montrent aucun signe certain d'une évolution actuelle.

Toutefois, Fyles nous a indiqué un pingo (numéro I sur la Figure 2) qui paraît présenter des traces d'évolution. Appartenant au type B de la Figure 4, il montre un sommet plus aigu au-dessus d'une forme générale de loupe. Ce sommet est dépourvu de lichens et ce fait suggère une évolution récente. Cette observation n'est cependant pas convaincante. La pente la plus forte de ce pingo ne dépasse pas 20 degrés et ne justifie donc pas une évolution plus rapide. La présence d'un sommet plus aigu où la couverture neigeuse est totalement absente pendant l'hiver ne favorise pas la conservation des lichens. Enfin, ce pingo, isolé au milieu d'une région très plane, est un excellent observatoire et il était, lors de notre passage, marqué de nombreuses traces de caribous. Ces animaux, en retournant les cailloux sous leurs pas, contribuent certainement à expliquer la rareté des lichens sur ce sommet. Au total, cette observation ne suffit pas à prouver que ces pingos grandissent de nos jours.



Coupe dans un pingo (Figure 7)

Du 16 au 23 juillet 1966, nous avons dégagé au moyen d'une pompe, une coupe dans le pingo numéro II sur la Figure 2. Situé au sommet d'une colline, ce pingo a été choisi parce qu'il présentait des conditions favorables à l'utilisation de la pompe, c'est-à-dire une pente suffisante et la proximité d'un petit lac temporaire fermé par un névé.

Le fait principal est la présence, entre 1.20 et 3 m de profondeur, d'une masse de glace continue. Il s'agit généralement d'une glace pure transparente et constituée de cristaux ayant de 0.5 à 2 cm de longueur, sans orientation préférentielle. Nous pensons qu'il s'agit de la glace même du pingo.

Ce noyau de glace a soulevé, en les déformant légèrement, les couches sablo-graveleuses de la formation de Beaufort. Ces dépôts, bien stratifiés et comprenant beaucoup de débris de bois, paraissent bien en place. A première vue, la masse de glace semble suivre un joint de stratification. Un examen plus détaillé montre qu'il n'en est rien: elle tronque les couches surincombantes. En deux endroits seulement, et chaque fois sur une longueur ne dépassant pas 1 m, existe à proximité de la glace une petite couche d'argile d'environ 0.5 cm d'épaisseur. Ailleurs, des sables et des graviers surmontent directement la glace.

A l'endroit marqué 5 sur la Figure 7, la glace montre des caractères différents. Elle présente une allure verticalement stratifiée, les inclusions sont beaucoup plus nombreuses d'où sa couleur blanche et elle est pénétrée à la partie supérieure de fines stries verticales de sable. Il s'agit là d'un coin de glace (ice wedge) qui correspond en surface à l'une des légères dépressions qui dessinent le réseau polygonal décrit précédemment. A proximité de ce coin de glace, les couches sont très déformées et dessinent un synclinal pincé, sans doute en relation avec la croissance de cette structure.

La pente extérieure qui est en fait le versant d'une vallée est constituée de sables et de graviers remaniés et descendus sur la pente. En 3, un gros bloc que nous pensons être un erratique — car il paraît dépasser la compétence du courant d'eau qui a amené la formation de Beaufort — semble indiquer que ce dépôt de pente a une épaisseur de près de 1.50 m.

A la partie supérieure de la coupe, plusieurs coins de sable et de graviers apparaissent. Ils ne dépassent pas 1.2 m de profondeur tandis que leur largeur atteint au maximum 0.6 m. Développé dans la «zone active» du sol, ces structures ne comprennent pas de glace. Il s'agit de formes semblables aux *sand wedges* de Péwé (1959) ou aux *ground veins* des auteurs russes (Dylik, 1966). Au sein de ces coins, existe un triage net. Les éléments plus petits descendent plus rapidement que les éléments plus volumineux, dans les fissures qu'ouvre chaque

année la rétraction thermique du sol. L'existence et le développement concomitant de coins de glace dans le permafrost et de coins de sable et de graviers dans la «zone active», paraissent pouvoir s'expliquer par la différence de teneur en glace qui permettrait à la couche superficielle, en raison de sa moindre cohésion et de sa faible épaisseur, de s'ouvrir en un réseau de polygones à mailles plus petites que celles séparant les coins de glace (Pissart, 1967).

Dans un autre pingo (III sur la Figure 2), une section a été également réalisée. Ne dépassant pas 2 m de profondeur, elle n'est pas parvenue jusqu'au noyau de glace du pingo. Des coins de sable et de graviers y découpaient également la «zone active».

INTERPRÉTATION, GENÈSE ET ÂGE DES PINGOS

Résumons d'abord brièvement les principales observations dont l'explication de la genèse et de l'âge de ces pingos doit rendre compte.

(a) Leur disposition en deux lignes parallèles, qui ne sont ni en relation avec la topographie, ni avec l'hydrographie, ni même avec une quelconque structure visible en surface.

(b) Leur apparente stabilité actuelle: sauf dans un cas douteux, aucun mouvement ne semble se produire de nos jours.

(c) Leur volume parfois appréciable: le plus grand de ces pingos a élevé une masse de plus de 150,000 mètres cubes (m^3) au-dessus de la surface du sol. Si cette masse provient de l'augmentation de volume consécutive à la congélation d'eau en système fermé, la quantité d'eau qui lui a donné naissance devait être neuf fois supérieure, soit atteindre 1,350,000 mètres cubes (m^3).

(d) Leur âge postérieur à la grande glaciation qui a recouvert l'île, car ils sont parfois localisés au sein des chenaux creusés par les eaux de fonte de ce glacier.

Il est absolument indiscutable que ces pingos ne sont pas des formes nées de phénomènes se passant uniquement dans la partie tout à fait supérieure du sol. L'absence totale de relation avec les faits de surface l'établit définitivement. Il est en outre certain que leurs alignements sont dus à une structure géologique mais celle-ci doit être profonde. Il peut s'agir, soit de couches argileuses au sein de la formation de Beaufort, soit d'une structure géologique plus profonde développée sous cette formation. La première hypothèse est gratuite, tandis que la seconde, par contre, trouve un certain appui dans la carte géologique de Tozer et Thorsteinsson. En effet, la carte que nous avons reproduite (Figure 1) montre que le substratum est affecté de failles; si celles-ci ont presque toutes une direction nord-sud, qui ne correspond pas à l'orientation des lignes de pingos reconnus, il en est cependant une autre orientée et localisée près du lac Landing qui semble se trouver dans le prolongement de la suite de buttes méridionales. Il nous paraît de ce fait possible que les deux alignements observés jalonnent des lignes de failles masquées sous l'épaisseur de près de 50 m des sables et graviers de la formation de Beaufort.

Si l'on admet que ces pingos sont en relation avec des failles affectant le socle, deux hypothèses peuvent être invoquées pour expliquer leur naissance. La première consiste à croire que les failles ont permis la venue d'eau profonde, la seconde, que les failles ont déterminé la présence de véritables pièges géologiques retenant captive, dans les sables de Beaufort, une masse d'eau qui, en se congelant en système fermé, a donné les injections observées.

La première de ces hypothèses, venue d'eau profonde depuis ces failles et à travers le permafrost, est à priori très satisfaisante, l'épaisseur de la formation de Beaufort surincombante permettant de comprendre pourquoi l'alignement des pingos n'est pas parfait.

Par ailleurs, la dimension des formes que nous avons observées correspond bien à celle de pingos dus à la montée d'eau venant de la partie inférieure du permafrost puisque pour Shumskii (1959), ce type de forme atteint 10 à 12 m et parfois même 15 à 17 m. Toutefois, cet auteur souligne que ce type de butte de glace d'injection n'existe qu'en bordure de la zone à permafrost, là où l'épaisseur du sol toujours gelé est faible. Or, quand on se souvient que sur l'île Melville voisine, le permafrost à une épaisseur de plus de 500 m et qu'il est vraisemblablement aussi profond ici, cette hypothèse perd son attrait. Il est en effet peu probable que de l'eau ait pu trouver un chemin au travers d'une telle épaisseur de terrain gelé. Il serait par ailleurs tout à fait gratuit d'admettre que le permafrost soit ici moins épais, car rien ne conduit à penser que le gradient géothermique soit localement plus élevé.

Accepter que le permafrost épais actuel constitue réellement une barrière à la venue d'eau profonde, conduit à penser que ces formes sont nées avant l'apparition de cette barrière, soit peut-être au début du Wisconsin. Rien ne s'oppose en effet à ce que nous considérions ces pingos comme très anciens. Il est possible que ce soit l'établissement du permafrost lui-même qui, comme dans les pingos du type Mackenzie, ait déterminé l'apparition d'enceintes fermées et ait donné par la suite la pression nécessaire aux injections d'eau vers la surface. Dans ce cas, les alignements correspondraient à des «pièges» de nappe aquifère qui seraient peut-être également à mettre en relation avec la présence des failles dont nous avons parlé plus haut.

Seules, des recherches géophysiques déterminant à quoi correspondent en profondeur les alignements observés, semblent susceptibles d'apporter des éléments nouveaux capables de faire progresser la connaissance de la genèse de ces pingos.

Signalons de plus, qu'y voir des formes nées du refroidissement initial du climat n'est que reprendre l'explication proposée par Leffingwell en 1919 (p. 154) pour les pingos de l'Alaska.

De toute façon, leur localisation au sommet de l'île et loin de tout lac, fait de ces pingos indiscutablement des formes qui n'appartiennent ni au type Groenland, ni au type Mackenzie.

LES PINGOS SITUES AU BORD DE LA MER PRÈS DE LA BAIE SATELLITE ET DE L'INLET INTREPID

Des pingos d'un type entièrement différent ont été observés dans deux baies localisées aux points 2 et 3 de la Figure 1 et situées, l'une au nord-ouest de l'île au fond de la baie Satellite, l'autre dans un golfe secondaire de l'inlet Intrepid. Ces pingos sont apparus d'un côté comme de l'autre à une altitude très proche du niveau actuel de la mer et au milieu de dépôts alluviaux. Leur genèse est liée à cette position. Il est donc nécessaire de décrire les complexes géomorphologiques où ils se localisent.

La baie Satellite

Comme il est possible de l'apercevoir en partie sur la Figure 8, un grand glacis s'étend à l'est de la baie Satellite sur une largeur qui a en moyenne 2 km. Il a été suivi depuis l'extrémité nord de la baie sur une longueur de près de 10 km; il se continue donc en dehors de la Figure 8 sur près de 5 km. Il s'agit d'une plaine d'épandage, de profil légèrement concave, qui se poursuit vers l'amont par de larges vallées mortes. Sa pente générale varie de 0.6 degrés au sommet à 0.3 degrés à l'aval. Cette diminution d'inclinaison s'accompagne d'une diminution de la dimension des cailloux qui en recouvrent la surface. La plus grande longueur des gros éléments passe progressivement de 20 cm de longueur en *Y* sur la Figure 8, à seulement 8 cm, 1.5 km en aval soit en *X* sur la même Figure. De même entre *V* et *W*, la plus grande dimension des cailloux diminue progressivement et la médiane de 5 mesures de centile effectuées en surface tous les 200 mètres ont donné les valeurs suivantes: 12.5cm, 12.5cm, 11.5cm, 11cm, 10cm, 8.5cm, 6cm, 7.5cm, 4.5cm. Ailleurs, sur cette plaine d'épandage glaciaire existe une diminution générale de la taille des plus gros éléments, mais elle est beaucoup plus irrégulière, des apports des versants y occasionnent des perturbations. En outre, des emboîtements de niveaux existent localement comme par exemple celui de la partie *T*, en contrebas par rapport aux surfaces situées de part et d'autre.

Le glacis a, par ailleurs, au débouché des vallées d'amont une allure générale de cône très surbaissé que soulignent les polygones de tundra; ceux-ci sont en effet quadrangulaires et leurs bords suivent deux directions: les uns s'allongent selon la ligne de plus grande pente et ont un tracé rayonnant, les autres suivent plus ou moins les courbes de niveau et dessinent de ce fait des portions de cercle dont le centre est situé au débouché des vallées.

Ce grand glacis est inexplicable par la simple érosion normale. Le bassin des vallées qui y débouchent est en effet dérisoire, leur longueur en amont ne dépassant généralement pas 2 km. Par ailleurs, la ligne de partage des eaux de l'île est elle-même très proche, à environ 4 km à l'est, et de ce fait, aucune capture ou changement dans le drainage ne peuvent être envisagés pour expliquer les grands débits dont nous retrouvons les traces.

Pour ces raisons, nous croyons que ce grand glacis est une plaine d'épandage glaciaire, trace

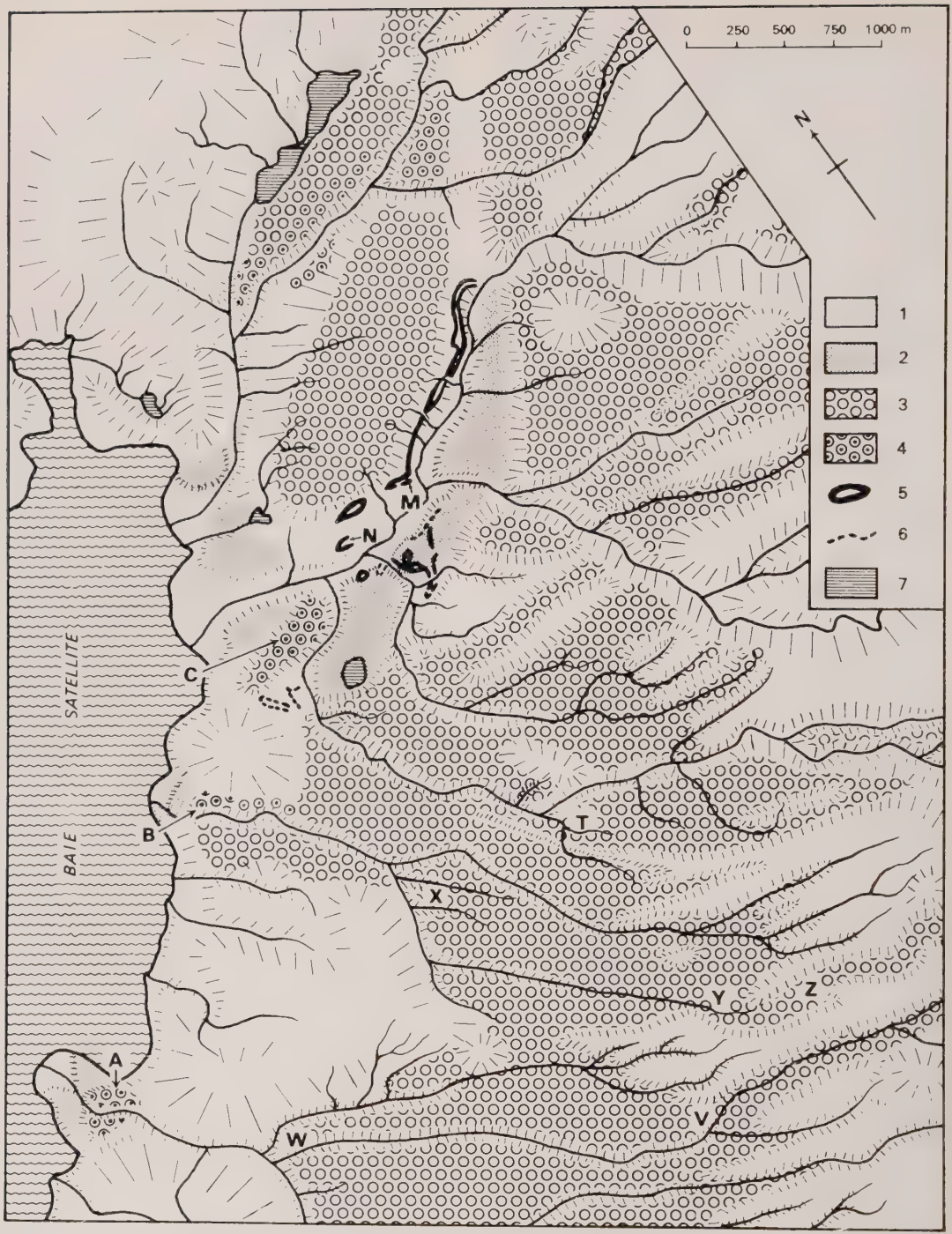


FIGURE 8. Croquis géomorphologique de la côte nord-est de la baie de Satellite où se localisent les pingos étudiés. Cette carte a été dessinée d'après les photos aériennes.

1. Lits majeurs des rivières.
2. Deltas et terrasses situés à environ 3.50 m au-dessus du niveau de la mer et des lits des rivières.
3. Plaine d'épandage glaciaire.
4. Dépôts deltaïques (avec foreset beds) raccordés à la plaine d'épandage glaciaire et dont les sommets sont au-dessus du niveau marin actuel de 10.7 m en *A*, de 13.80 m en *B* et de 12 m en *C*.
5. Pingo actuel, en fusion, comme le montre le centre blanc représentant le creux central.
6. Trace de pingo apparaissant seulement par la déformation des couches fluviatiles.
7. Lac.

d'une glaciation importante venue de l'est qui a amené sur l'île Prince-Patrick de nombreux erratiques. Cette glaciation est toutefois ancienne car cette plaine d'épandage est incisée profondément par de nombreux cours d'eau souvent de débit insignifiant.

La surface de ce dépôt fluvio-glaciaire se prolonge vers l'aval jusqu'à la côte actuelle. Elle se termine en cet endroit à environ 12m au-dessus du niveau de la mer par des dépôts deltaïques caractéristiques où apparaissent très bien les *foreset beds*. Les altitudes de 10.70 m, 13.80 m et 12.00 m correspondent aux sommets des extrémités des glacis où existent des *foreset beds*, soit aux points A, B, et C de la Figure 8. Il ne nous a pas été possible d'établir si ces variations sont la conséquence d'un changement du niveau de la mer au cours de l'apparition du dépôt fluvio-glaciaire.

Cette observation des dépôts deltaïques, répétée en quatre endroits s'échelonnant au fond de la baie sur 10 km, établit clairement que le niveau de la mer devait se trouver à un niveau proche de + 12 m lors du recul du glacier. Deux lacs de plusieurs centaines de mètres de longueur, dont l'un est visible sur la Figure 8, et qui paraissent assez profonds, existent dans ce glacis. Leur explication est délicate. L'érosion postérieure ne peut en rendre compte et ils sont dus, soit à des culots de glace morte, soit plus simplement à des parties non entièrement colmatées lors de la formation du dépôt fluvio-glaciaire.

Des deltas inférieurs situés à environ 3.50m au-dessus du niveau de la mer existent en contrebas; ils ont été observés en six endroits, entre 3.25 et 4 m; trois d'entre eux apparaissent sur la Figure 8. Dans la partie inférieure de la vallée où se localisent les pingos que nous allons étudier, existe un certain nombre de basses terrasses qui se raccordaient à un ou plusieurs niveaux marins compris entre 2.50 et 3.50 m. La surface de ces terrasses est irrégulière: elle est déformée par des polygones de fente de gel, si bien qu'il nous a été impossible de décider avec certitude si tous les lambeaux appartenaient au même niveau, et s'ils se raccordaient tous aux deltas situés à

FIGURE 9. La baie Satellite; Photo prise le 18 juin, 1965.

1. Pingo en forme de volcan (diamètre 50 m, hauteur 3 m).
2. Pingo N de la Figure 8. Tronqué par l'érosion latérale de la rivière. (hauteur 7 m).

FIGURE 10. Extrémité ouest du long pingo de la baie Satellite. Le pingo est ici tronçonné par de petits cours d'eau. La coupe montrée par les Figures 14 et 15 et inscrite M sur la Figure 8 est indiquée d'une flèche.

l'altitude de 3.50 m que nous venons de mentionner plus haut. Ces raccords étant cependant très probables, les deltas et terrasses de 3.50 m ont été représentés de manière identique sur la Figure 8.

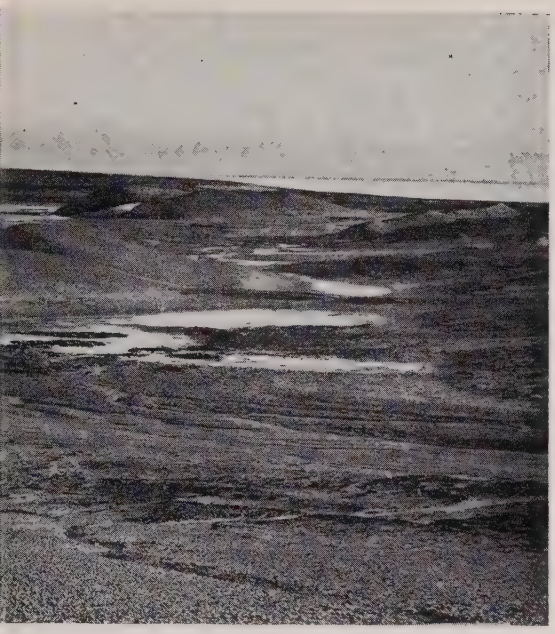
Description des pingos

Les pingos situés au fond de la baie Satellite sont relativement peu nombreux. Leur différence d'aspect, visible sur la Figure 8, permet de les grouper en trois catégories et de distinguer selon leur forme en plan, des pingos ronds, ovales et très longs. De plus, existent des restes de pingos complètement ou à peu près complètement fondus, dont la forme originelle est parfois difficile à reconstituer.

Un seul pingo présente une forme conique tout à fait classique, avec en son sommet une dépression qui, dans sa position, fait penser au cratère d'un volcan. Ses dimensions sont cependant réduites puisque cette butte a seulement 50 m de diamètre et 3 m de hauteur (Figure 9).

Deux buttes un peu plus élevées (6 à 7 m), et présentant également à la partie supérieure des dépressions semblables, ont une forme en plan ovale. Elles constituent une transition avec les pingos très allongés qui sont les formes les plus importantes que nous avons reconnues. La plus grande de ces formes se présente comme une longue ride semblable à un esker (Figure 10). Sa longueur atteint en effet 1.300 m tandis que sa largeur est variable, mais reste comprise entre 40 et 70 m, et sa hauteur ne dépasse pas 8.75 m. Elle diffère extérieurement d'un esker en ce que sa partie médiane est occupée par une dépression s'allongeant sur la majeure partie de la butte (Figure 11). C'est cette dépression axiale, trace de fusion indiscutable, qui a permis de reconnaître sur photos aériennes qu'il s'agissait d'un pingo; cette interprétation a été confirmée, comme nous le verrons plus loin, par la mise à jour en deux endroits distincts du noyau de glace d'injection. Localement, ce long pingo en fusion montre non seulement une dépression centrale, mais un relief mamelonné (Figure 12) qui ressemble à celui des grands pingos du sommet de l'île (Figure 5).

Outre ces traces de fusion dont nous venons de parler, ce long pingo est incisé par des vallons transversaux qui recoupent cette butte perpendiculairement à son grand axe (Figure 10). Ils sont l'œuvre des eaux descendant de la



terrasse voisine. Rien ne permet de savoir si cette érosion a été concomitante de l'apparition du pingo, ou lui a été postérieure.

A côté de ces formes en fusion, mais toujours en relief par rapport à la topographie voisine, existent des pingos beaucoup plus évolués dont il ne reste que peu de traces. Ils se groupent sur la rive gauche de la rivière principale, et l'identité avec les autres structures apparaît principalement par l'allure redressée, presque verticale, que présente la stratification de part et d'autre d'un creux central peu apparent. La partie du noyau de glace située sous le niveau du sol est comprise dans le permafrost et de ce fait n'a vraisemblablement pas encore fondu. De là provient la différence d'aspect de ces formes avec les traces de pingos connus en Europe.

Localisation des pingos dans la topographie

Tous les pingos observés sont localisés nettement en contrebas de la plaine d'épandage présumée glaciaire. Ils se trouvent soit sur les terrasses inférieures que nous avons décrites, soit peut-être dans la plaine alluviale actuelle. Le pingo circulaire en forme de volcan s'élève sur une terrasse qui domine la rivière de 3.10 m, tandis que le très long pingo est sur une grande partie de sa longueur au contact immédiat de la plaine alluviale actuelle. En plusieurs endroits, il est d'ailleurs érodé vigoureusement par la rivière.

De l'ensemble de nos observations, il est

FIGURE 11. Même pingo de la baie Satellite. Vue de la dépression centrale (D), se poursuivant dans l'axe du pingo. La coupe montrée par les Figures 14 et 15 est indiquée par la lettre M.

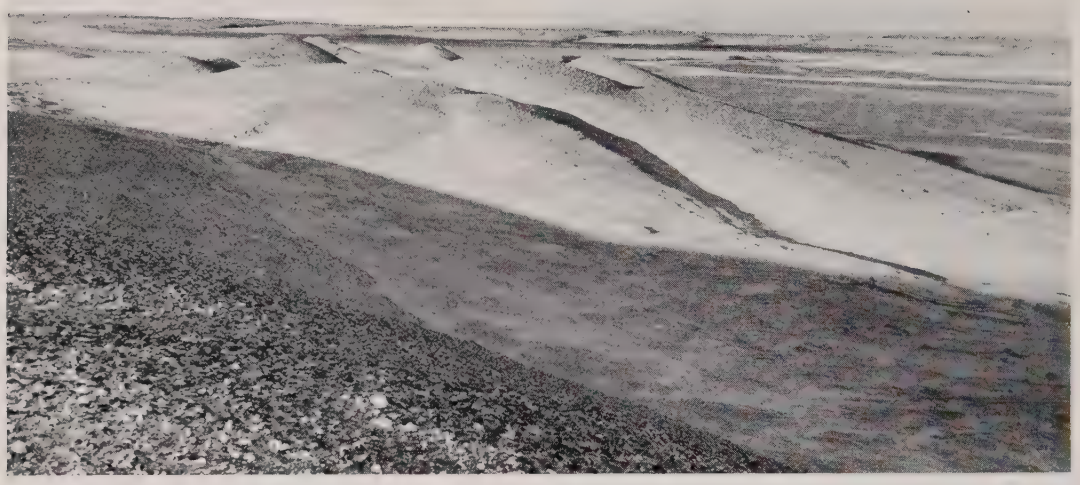


FIGURE 12. Pingo de la baie Satellite. Aspect mamelonné résultant de la fusion irrégulière du noyau de glace et rappelan celui de certains pingos observés au sommet de l'île (*voir* Figure 5).

impossible de dire si certaines de ces formes sont apparues dans la plaine alluviale actuelle ou si elles sont toutes nées sur les basses terrasses. Les formes topographiques ne permettent pas de dire s'il existe deux générations de formes apparues à des niveaux différents, ou seulement un seul groupe de pingos du même âge. L'ensemble des faits suggère cependant que deux ensembles distincts existent, l'un constitué des formes assez bien conservées situées près de la rivière actuelle, l'autre comprenant les structures presque totalement fondues qui sont réparties principalement sur les terrasses de la rive gauche.

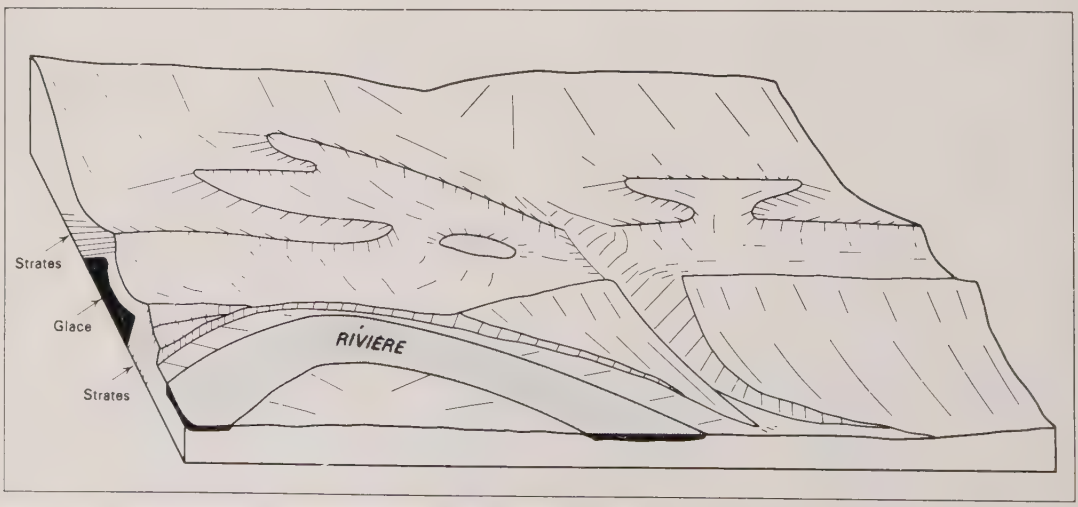


FIGURE 13. Croquis montrant la structure complexe que présente parfois le long pingo de la baie Satellite. De part et d'autre du noyau de glace, les couches sablo-graveleuses originellement horizontales ont été redressées.

FIGURE 14. Coupe transversale dans le long pingo de la baie Satellite (point M de la figure 8). Cette coupe est décrite sur la Figure 15. Le noyau de glace d'injection actuellement en fusion est indiqué d'une flèche.

Coupes observées

Des coupes nombreuses ont été observées dans ces pingos. Beaucoup d'entre elles ont été dégagées à la pelle (avec l'aide de Leif Lundgard en 1965 et de Raymond Richard en 1966 que nous remercions ici) et n'ont montré que les 60 cm supérieurs du sol, épaisseur dégelée lors de notre séjour en cet endroit au début du mois d'août 1965. Deux entailles plus importantes ont toutefois été creusées par l'écoulement de l'eau de lacs localisés au sommet de pingos, écoulement que nous avons provoqué en creusant un petit chenal permettant au premier flot de s'écouler. Deux autres plus importantes ont été réalisées grâce à la pompe dont nous avons disposé en 1966. Ces entailles ont mis à jour la glace d'injection et ont confirmé que la disposition des couches est très redressée sur les versants des pingos. Cette inclinaison des strates sur les flancs est générale. Elle a été vérifiée en de très nombreux endroits car elles apparaissent en affleurement au sommet de la crête limitant les dépressions nées de la fusion. Ainsi, il est possible de suivre les couches redressées et de connaître la structure du pingo. Celle-ci n'est pas toujours très simple. Parfois en effet, le pingo n'est pas constitué d'une loupe de glace de forme simple mais bien d'une masse présentant des apophyses comme l'indique la Figure 13.

La plus belle de toutes les coupes examinées était le résultat de l'érosion latérale de la rivière. La Figure 14 permet de voir le profil observé en 1965 et dont la localisation est donnée sur les Figures 8, 10 et 11 par la lettre *M*. Cette coupe dévoilait la structure de la moitié du pingo le plus long car elle s'étendait transversalement depuis l'extérieur de la butte jusqu'à sa dépression médiane. En 1966, une coupe a été dégagée dans l'autre moitié du pingo et a permis de voir le profil transversal complet de cette structure que nous présentons sur la Figure 15.

Le noyau de glace

La première observation montre que la dépression centrale correspond à une masse de glace. Celle-ci est constituée de cristaux atteignant 2 cm de longueur qui apparaissent clairement à l'oeil nu par l'orientation différente des inclusions gazeuses qui y sont parti-

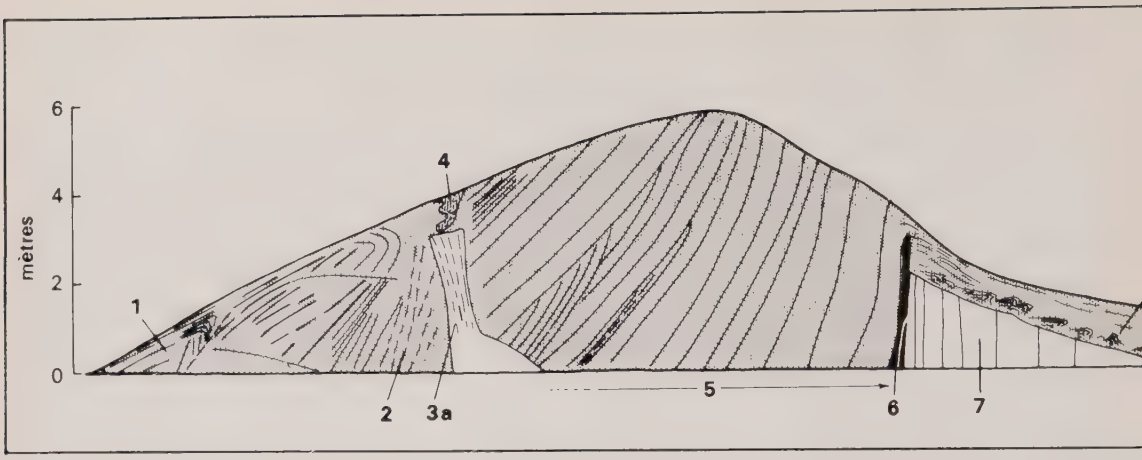


FIGURE 15. Coupe au travers du long pingo de la baie Satellite (*voir* photos 14 et 16).

1. Sables et cailloux présentant un litage mal défini: dépôts de pente.
2. Couches verticales, indistinctes.
3. a) Coin de glace (structure de polygone de fente de gel).
   b) Coin de glace et de sable (structure de polygone de fente de gel).
4. Coins de graviers correspondant, dans la zone active aux structures de fente de gel.
5. Couches de sables et de graviers dont la granulométrie diminue dans la direction de la flèche.
6. Argile noire comprenant des foraminifères marins.
7. Glace d'injection du pingo.
8. Dépôts de pente.

culièrement nombreuses. Ces cristaux se présentent exactement comme les cristaux de glace d'injection que Fritz Müller (1959, Figure 15 b) a observé dans un pingo du Groenland. A cause des multiples inclusions gazeuses, la teinte de la glace est généralement blanchâtre; localement, la glace présente toutefois moins d'inclusions et est de ce fait, beaucoup plus transparente. La partie extérieure de la masse de glace, en contact avec les couches verticales de bordure, montre sur une largeur de 1.50 m d'un côté et de 3 m de l'autre, une stratification qui lui est parallèle (Figure 16). De l'extérieur en direction du centre, cette stratification est due, tout d'abord, sur 50 cm, à des lits sableux généralement très fins et plus loin à une coloration rougeâtre de la glace donnée par des dépôts d'oxydes de fer. Ces sels de fer sont particulièrement abondants à la partie supérieure du noyau de glace, au contact glace-dépôts de couverture où ils paraissent s'accumuler au moment de la fusion. Ils sont par ailleurs aisément explicables par la précipitation des sels contenus dans l'eau au moment où elle se congèle (Cailleux 1964); Ek et Pissart 1965). Cette allure stratifiée est locale et n'a pas été retrouvée ailleurs. Elle témoigne de la croissance lente du noyau de glace au début de sa formation par arrivée successive de quantités d'eau peu importantes.

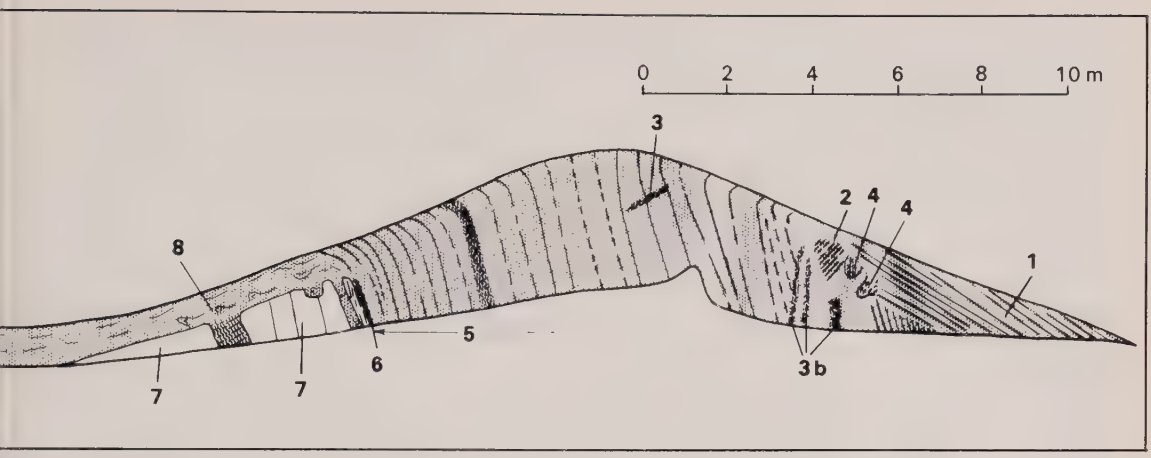
Une mince veine de glace très différente, dont les cristaux sont orientés perpendiculairement à la stratification, se détache à l'extrémité gauche de la masse de glace principale et pénètre obliquement dans l'argile voisine. Il s'agit vraisemblablement de glace de ségrégation.

A droite, la masse de glace comprend deux couches de sable disposées parallèlement à la stratification des formations soulevées et qui paraissent en faire partie.

Comme nous l'avons dit précédemment, un noyau de glace identique à celui-ci a été observé au coeur même de toutes les buttes étudiées, partout où une coupe assez profonde a été dégagée, c'est-à-dire en cinq endroits différents. Ces observations prouvent sans hésitation possible que les dépressions centrales des buttes examinées sont dues à la fusion du noyau de glace.

Le matériel entourant ce noyau de glace

Le matériel stratifié et repoussé par ce noyau de glace est principalement sableux et graveleux. Toutefois, plus on se rapproche du noyau de glace lui-même, plus le sédiment est fin,



pour être même franchement argileux au contact de celui-ci. Remarquons que P. A. Shoumsky (1955, p. 121) signale que la glace d'injection apparaît ordinairement au contact de couches perméables/couches imperméables, comme c'est le cas ici. Des modifications de couleur accompagnent les changements de granulométrie car avec l'apparition de la fraction fine, les couches sont de plus en plus sombres, une teinte bleuâtre très foncée remplaçant la couleur jaune des sables.

Ces modifications générales de granulométrie et de couleur, bien apparentes lorsque l'on considère l'ensemble de la coupe, ne sont pas visibles lorsqu'on examine une partie de celle-ci. En effet, dans le détail, des bancs plus clairs

FIGURE 16. Détail de la photo 14 montrant le noyau de glace d'injection du long pingo en fusion. Remarquez l'allure générale stratifiée de la glace due, à gauche, à des parties minérales et, à droite, à des oxydes de fer rougeâtres.

et plus foncés se succèdent sans ordre apparent. Ajoutons que les couches bleuâtres foncées deviennent brunes lorsqu'elles sont exposées à l'air et que cette couleur noirâtre n'a donc été observée qu'en creusant dans le permafrost. L'étude microscopique d'une préparation de ces sédiments a montré que la couleur noire du dépôt est due à la présence de substances organiques souvent reconnaissables (pollens, feuilles de mousse, etc. . .) qui ont été soustraites dès la sédimentation à toute oxydation ou altération. Les couches argileuses surmontant la glace comprennent des tests de foraminifères marins très semblables à ceux qui existent dans l'Arctique actuel. Les espèces observées *(Buccella Frigida, Spiroplectammina Biformis, Elphidium Incertum, E. Orbiculare, Asterellina Pulchella)* sont des formes côtières typiques, d'eaux peu profondes. L'étude des foraminifères contenus dans nos échantillons a été effectuée très aimablement par G. Vilks de l'Institut Océanographique de Bedford (Dartmouth, Nouvelle-Ecosse).

En outre, au sein des couches sableuses existent très souvent des débris de bois. Ceux-ci sont remaniés depuis la formation de Beaufort qui en contient beaucoup. Ils ne fournissent aucune indication quant à l'âge des sédiments qui les entourent. Ces dépôts de sables, de sables graveleux et d'argile sont très bien lités. Localement ils présentent une stratification entrecroisée caractéristique. Toutefois, comme ces couches ont été déformées, leur allure originelle est difficile à reconstituer. Les strates actuellement présentent une inclinaison variant de 80 à 40 degrés.

Des fentes de gel existent aux deux extrémités de la coupe. A gauche, un coin de glace dont la longueur est de 50 cm paraît faussement s'élargir à la partie inférieure, du fait du gauchissement du profil. A droite, plusieurs fentes de gel à remplissage de sable et de glace ont été aperçues. Au-dessus de ces structures, l'aspect est fort complexe. Des masses diverses de graviers et de sables paraissent y avoir pris place par descente du matériel surincombant. Ce phénomène s'est sans doute produit lorsque, à la suite de l'érosion du pingo, les parties supérieures de ces fentes de gel ont été comprises dans la zone active et ont fondu. Au sein de ce matériel, à 1,5 mm de la surface actuelle, nous avons trouvé des débris organiques qui ont été datés au carbone-14 dans le laboratoire de la Commission géologique du Canada (échantillon n° GSC 854). Leur âge est de 7 090 ans ± 150 ans. Vu leur position, ces restes organiques paraissent beaucoup plus jeunes que le pingo lui-même.

Enfin, des dépôts de pente, présentant un litage mal défini, existent sur les parties extérieures du pingo; ils recouvrent à droite la masse confuse où ont été trouvés les débris organiques datés.

INTERPRÉTATION

De cette description, nous retenons principalement les interprétations suivantes:

(a) Les couches soulevées constituent une série continue de dépôts marins et fluviatiles originellement horizontaux. Il ne s'agit pas du substratum, c'est-à-dire de la formation de Beaufort, mais de sédiments déposés par la rivière.

(b) Ces couches ont été soulevées postérieurement à leur dépôt et une simple reconstitution géométrique permet d'affirmer que les couches les plus anciennes se sont déposées originellement à une profondeur d'au moins 10 m sous le lit actuel de la rivière.

(c) Les couches les plus anciennes de cette série, c'est-à-dire celles qui se trouvent à proximité du noyau de glace, sont constituées de sédiments fins qui se sont déposés en eau calme et ont une origine marine, comme l'atteste l'étude des foraminifères.

La forme très allongée du pingo principal est inhabituelle, nous l'avons déjà signalé. Peu d'auteurs ont décrit des pingos de cette espèce. Le plus ancien article mentionnant des formes semblables est, à notre connaissance, celui de Porsild qui, en 1938, a parlé de pingos très longs s'étirant parallèlement à la ligne de plus grande pente dans la presqu'île de Seward en Alaska. Stager (1956, p. 15) et aussi J. Ross Mackay (1962) ont également signalé dans le delta de Mackenzie, l'existence de pingos semblables à des eskers. Enfin, Lewis (1962) a récemment décrit dans la revue *Arctic* un petit pingo allongé s'étirant dans une plaine alluviale d'une rivière de l'Alaska.

La forme allongée de ces pingos n'a pas été expliquée à ce jour et rien dans la littérature ne permet de rendre compte directement des formes de l'île Prince-Patrick. Plusieurs hypothèses sont plausibles mais aucune n'est cer-

taine. A première vue, il semble très probable que ce long pingo correspond à un ancien cours de la rivière. Nos observations ne nous permettent pas d'élucider complètement les circonstances qui ont donné naissance aux pingos que nous venons de décrire. Deux hypothèses différentes peuvent être défendues; nous les exposons ci-dessous.

La première consiste à voir dans les couches soulevées par les pingos, des formations fluviatiles et marines antérieures à l'apparition de la plaine d'épandage glaciaire qui a nivelé à environ 12 m au-dessus du niveau marin actuel, la zone où se localisent les pingos. Ces formations ne sont pas, en tous cas, les dépôts de la plaine d'épandage glaciaire, car le centile est beaucoup moins grand, et il est comparable à celui des alluvions actuelles du cours d'eau. Dans ce cas, ces formations débarrassées des dépôts fluvio-glaciaires mentionnés ont seulement été soulevées par la croissance des buttes de glace d'injection et ne témoignent en rien des conditions qui ont précédé l'apparition de ces formes. La genèse des pingos serait alors la suivante: à la suite de la baisse du niveau marin, la vallée, les terrasses et la plaine alluviale actuelle auraient été façonnées. Des conditions climatiques plus chaudes et une meilleure alimentation du cours d'eau auraient permis le dégel superficiel du permafrost sous le lit de la rivière sur une profondeur de plusieurs dizaines de mètres. Un refroidissement survenant alors, la reconquête par le permafrost de la zone dégelée a emprisonné, au sein du sol gelé, une enceinte fermée de sables gorgés d'eau permettant, par le mécanisme des pingos du Mackenzie, l'injection d'eau vers la surface.

Cette première hypothèse nous paraît peu vraisemblable. En effet, le cours d'eau dont l'écoulement actuel ne dure guère plus de quelques semaines par an est absolument incapable de faire fondre le permafrost. Un réchauffement climatique très important aurait été nécessaire pour que l'écoulement de ce petit cours d'eau dure assez longtemps pour permettre ce dégel du sol. Celui-ci aurait d'ailleurs dû se produire sur une profondeur de plusieurs dizaines de mètres, si l'on calcule le volume du sable gorgé d'eau qui, en se congelant, a donné la masse des pingos.

La seconde hypothèse que nous croyons plus probable, encore que nous reconnaissions que les objections formulées soient insuffisantes pour rejeter définitivement la première, est la suivante. Elle consiste à voir dans les couches soulevées par les pingos, des formations ayant remblayé un golfe marin ou plus exactement une ria dont l'envahissement par les eaux aurait permis la fusion du permafrost. Postérieurement au façonnement de la plaine d'épandage glaciaire, qui nivelait le tout au dessus de l'altitude + 12 m, l'érosion aurait, non seulement creusé jusqu'au niveau de la plaine alluviale actuelle, mais aussi façonné une vallée plus profonde et cela, en relation avec une baisse du niveau marin, l'amenant en contrebas de son niveau actuel. Les formations soulevées correspondraient au colmatage du golfe qui serait apparu à la suite d'un mouvement positif cette fois du niveau de la mer. Sans cette «ria», le permafrost aurait évidemment fondu, au moins partiellement.

En d'autres termes, cette hypothèse prévoit les stades suivants:

(a) Le façonnement d'une plaine d'épandage glaciaire nivelant la région où se trouvent les pingos à une altitude supérieure à + 12 m

(b) L'abaissement du niveau marin, environ 10 m, sous le niveau actuel et la dissection de cette plaine d'épandage à partir de ce niveau de base

(c) Une élévation ultérieure du niveau marin l'amenant à sa position actuelle et créant une «ria». La pénétration des eaux marines dans la partie inférieure de la vallée y détermine la fusion au moins partielle du permafrost.

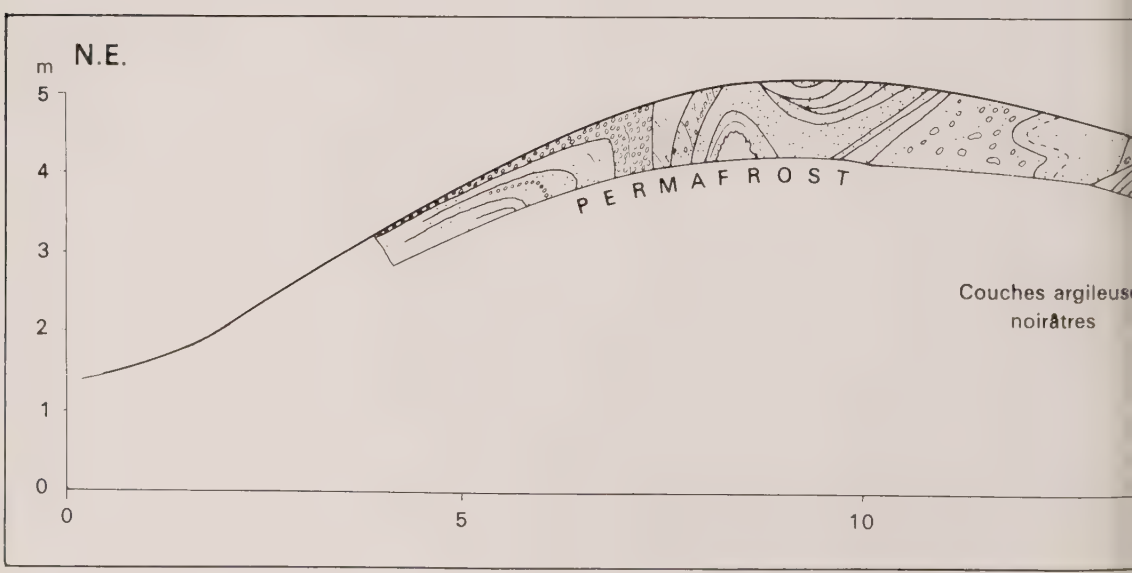
(d) Le colmatage de la «ria» et le rétablissement du sol gelé. La progression de celui-ci détermine l'emprisonnement entre le permafrost profond et le sol gelé superficiel d'une masse de sables gorgés d'eau.

(e) La congélation de ces sables gorgés d'eau engendrant l'injection d'eau sous pression vers la surface, par le même mécanisme que celui qui a donné naissance aux pingos du Mackenzie.

Cette hypothèse explique la variation granulométrique observée dans les formations surmontant le pingo. Elle paraît recevoir en outre un appui considérable dans le peu d'extension (voir Figure 7) des deltas actuels qui débouchent dans la baie Satellite. En effet, il est

FIGURE 17
Croquis géomorphologique dessiné d'après photos aériennes, montrant la localisation des pingos observés près de l'inlet Intrepid.
1. Plaine alluviale actuelle.
2. Basse terrasse.
3. Terrasse élevée de plus de 10 mètres au-dessus du niveau marin.
4. Pingo.
5. Lac.

B indique la localisation de la coupe donnée à la Figure 18.



étonnant de constater que l'encaissement de plus de 10 m de toutes les rivières dans la plaine d'épandage glaciaire ait seulement façonné dans cette baie pratiquement sans marée, des deltas qui pour les rivières principales n'atteignent que quelques centaines de mètres. Il y a là une discordance entre le cubage enlevé et la masse déposée qui ne paraît pouvoir se résoudre qu'en admettant l'existence sous le niveau marin actuel de deltas plus étendus mais complètement submergés.

Cette hypothèse est encore supportée par la présence à 100 km de là, près de l'inlet Intrepid de pingos identiques qui paraissent s'expliquer d'une manière semblable.

L'inlet Intrepid

A 95 km au sud-ouest de la baie Satellite, dans une baie s'ouvrant sur l'inlet Intrepid (Point 3 de la Figure 1), existe également un complexe de pingos qui présentent, avec ceux que nous venons de décrire, une grande similitude. Celle-ci réside dans la localisation de ces pingos au coeur d'un complexe de terrasses situé à l'embouchure d'un cours d'eau, et dans le fait que ces pingos sont apparus au niveau de la plaine alluviale actuelle, soit à une altitude très voisine de celle de la mer.

Le croquis donné à la Figure 17 montre mieux qu'une longue description, la localisation de ces formes et fait spécialement apparaître, ici encore, l'existence d'un pingo allongé semblable à ceux que nous avons trouvés près de la baie Satellite; il a une forme complexe, et est sapé par l'érosion latérale de la rivière qui, localement, l'a complètement détruit.

Les coupes que nous avons dégagées ont prouvé que cette butte allongée était bien un pingo car, comme le montre la Figure 18, un noyau de glace repose ici également en dessous de dépôts sableux fins noirâtres, comparables à ceux qui ont été trouvés près de la baie Satellite, dépôts qui témoignent d'une sédimentation en eau calme, dans un lac ou dans la mer. Comme près de la baie Satellite, ces dépôts fins sont noirâtres dans le permafrost, mais deviennent bruns quand ils sont exposés à l'air libre. Une couche de 30 cm de sables et de graviers existe ici entre la glace et le matériel fin. Aucun test de foraminifère n'a toutefois été observé dans ces couches noirâtres. Les dépots sablo-graveleux recouvrant ces couches fines ont une origine fluviatile certaine.

La disposition des strates est en général identique à celle vue dans les profils levés près de l'inlet Intrepid: la stratification est presque verticale à proximité du noyau de glace. Le synclinal observé dans la coupe donnée à la Figure 18 est un accident unique, qui n'a pas été retrouvé ailleurs. Au sommet de la partie la plus élevée du pingo, affleurent des débris du substratum mésozoïque, paquets rougeâtres de sables et de grès fossilifères, dont la présence au milieu des sables fluviatiles ne peut s'expli-

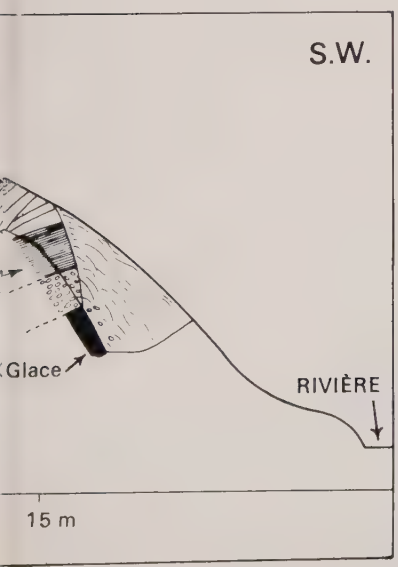


FIGURE 18
Coupe dans le pingo allongé de l'inlet Intrepid à la pointe *B* de la Figure 17 donnant la succession des couches, leur disposition et le noyau de glace d'injection. Cette coupe ne montre qu'un demi pingo, l'autre moitié ayant été détruite par l'érosion de la rivière.

quer qu'en admettant que le pingo a pris ici naissance dans la roche secondaire sous-jacente, et en a soulevé une partie.

D'après ces observations, nous retrouvons ici, comme près de la baie Satellite, un long pingo apparu à peu près au niveau de la plaine alluviale actuelle et contemporain d'un remblaiement ayant suivi une période de sédimentation en eau calme.

La similitude existant entre ce pingo et ceux qui ont été observés à 95 km au nord, constitue un argument de poids en faveur de l'hypothèse qu'ils sont nés à la suite de fluctuations du niveau marin qui ont affecté toute la côte de l'île. Les terrasses situées à plus de 10 mètres montrent l'existence d'une première phase pendant laquelle le niveau marin était plus élevé qu'actuellement. Par la suite, une descente du niveau de la mer sous l'actuelle altitude zéro a permis l'incision de ces terrasses. Une dernière fluctuation eustatique, ou un dernier mouvement du sol, a transformé cette entaille en une ria et engendré la fusion du permafrost. Le colmatage de cette ria par la mise en place des couches fluviatiles soulevées par le pingo, a permis le rétablissement du permafrost et l'apparition d'un «système fermé» donnant naissance au pingo.

La forme allongée de cette butte de glace d'injection correspondrait peut-être à l'entaille que la rivière aurait creusée antérieurement au relèvement du niveau marin. Le fait que le pingo ne se prolonge pas jusqu'à la mer, s'expliquerait ainsi: à l'extrémité aval, les eaux mises sous pression ont pu, par des couches souterraines, s'échapper vers la mer. Le pingo n'est donc apparu que lorsque cette issue a été fermée par le développement du permafrost, à moins que des couches imperméables n'aient déterminé elles-mêmes une enceinte fermée, dès le début du gel.

Autres Pingos sur l'île Prince-Patrick

A

A 23 km au sud-ouest de la station météorologique de Mould Bay, de l'autre côté de la baie (point 4 de la Figure 1) existe un pingo dont l'aspect extérieur ne laisse aucun doute quant à sa nature. En effet, ce pingo est en fusion et se présente comme une butte allongée ayant en son centre une dépression longitudinale discontinue. La morphologie est donc identique à celle qui a été décrite précédemment dans les régions de la baie Satellite et de l'inlet Intrepid. Toutefois, sa localisation dans la topographie est différente comme on peut l'apercevoir sur les Figures 19 et 20. Il est en effet situé au pied d'un versant abrupt haut de plus de 150 m, sur un cône de déjection. La pente de ce cône est comprise entre 6 et 3 degrés. Constitué de débris de grès et de schistes dévoniens qui proviennent du substratum local, ce pingo est le seul que nous ayons aperçu qui ne soit pas dans des sables et des graviers. La surface de la butte montre en effet uniquement des cailloux et des blocs dont la longueur dépasse parfois 1 m et qui sont emballés dans un matériel limoneux.

La forte pente des bords de la dépression centrale, atteignant localement 42 degrés, atteste que la fusion du centre du pingo est récente ou actuelle. Aucun écoulement ou suintement d'eau ne paraît toutefois sortir de cette butte. Du fait de sa situation au fond d'une vallée, au pied d'un versant haut de plus de 150 m, ce pingo peut provenir de l'injection d'eau mise en charge sur le relief voisin et

FIGURE 19
Photographie du pingo en fusion dont la Figure 20 montre l'aspect en plan.

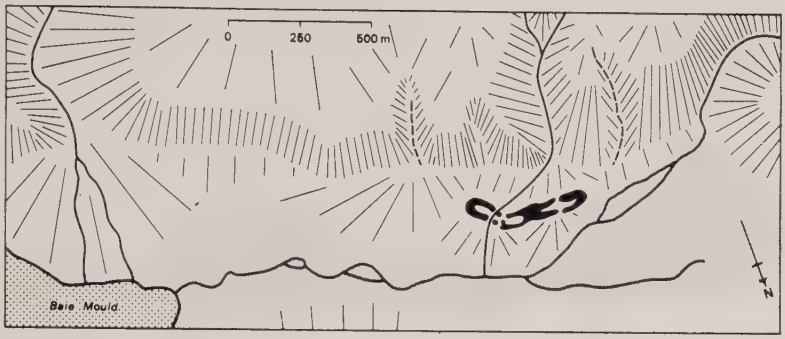


FIGURE 20
Croquis dessiné d'après photos aériennes et des levés de terrain montrant la forme et la localisation dans la topographie d'un pingo allongé et en fusion situé à 23 km au sud-ouest de la station météo de Mould Bay.

constituer de la sorte un exemple d'un pingo de type *Groenland*. Dans ce cas, comme il est cependant très improbable que pareil mécanisme ait pu se développer alors qu'existait le très profond permafrost actuel, il est vraisemblable que l'apparition de cette butte soit un phénomène très ancien.

B

Deux pingos, également très allongés, ont été observés à l'est du champ de pingos décrit en premier lieu dans cet article et situé à 23 km au nord-ouest de Mould Bay.

Le premier se trouve à l'emplacement du point 5 de la Figure 1 et s'allonge dans l'axe de la vallée sur plusieurs centaines de mètres: son origine est clairement indiquée par l'existence d'une dépression plus ou moins continue en son sommet. Sa hauteur maximum atteint 10.50 m. La genèse de ce pingo, situé dans l'axe d'une vallée importante façonnée vraisemblablement par les eaux de fonte glaciaire et s'étendant sur plusieurs centaines de mètres, n'a pas été comprise.

Le second pingo est localisé près de l'exutoire du lac Landing, à 16 km au nord-ouest de Mould Bay. Il s'agit d'un pingo allongé sur environ 100 m et large au maximum de 32 m. Comme la glace qui lui a donné naissance est à peu près complètement fondue, il se présente sous forme d'un bourrelet haut au maximum de 3 m, entourant une dépression centrale.

C

Enfin, quelques dizaines de petites buttes dues au gel existent à 60 km au nord de la station de Mould Bay (point 6 de la Figure 1), au sommet de l'île. Leur localisation est en cela identique à celle des pingos que nous avons décrits au début de cet article. Ces buttes sont, en effet, dispersées sur le plateau horizontal constitué des sables et graviers de la formation Beaufort, dans la zone de relief indécis où les eaux se partagent entre les deux versants de l'île.

Ces buttes sont généralement circulaires, leur diamètre varie entre 30 m et 70 m et leur hauteur est toujours très faible, la dénivellation maximum observée atteignant seulement 2.10 m. Ces buttes sont souvent découpées par des polygones de tundra et apparaissent sur les photos aériennes comme des taches sombres, presque noires, dues à ce que les lichens y sont plus nombreux et recouvrent presque tous les cailloux.

L'origine de ces formes n'est pas connue. Aucune relation avec la topographie n'a été observée et aucun alignement n'a été constaté. Ces buttes n'existent que dans cette partie restreinte de la formation de Beaufort. Leur petite dimension en fait des formes comparables aux «Bugors» et il n'est pas exclu qu'elles soient dues effectivement à la croissance de lentilles de glace de ségrégation dans les couches parfois limoneuses de ce plateau très calme, où l'écoulement de l'eau est difficile.

CONCLUSION

Ce travail établit l'existence d'au moins deux types distincts de pingos sur l'île Prince-Patrick, soit loin au-delà du cercle polaire arctique. Ils n'appartiennent ni au type Groenland ni au type Mackenzie, et montrent que la variété des types de pingos est plus grande que certains ne le pensaient. Cette étude souligne en outre que, indépendamment de toute fluctuation climatique, des modifications du niveau marin peuvent donner naissance à des buttes de glace d'injection.

Tous les problèmes que posent ces pingos n'ont pu être résolus. Le principal est celui de leur âge. Il sera peut-être connu un jour par datation au carbone-14 des débris organiques qui se trouvent parfois dans les couches fines surmontant le noyau de glace.

Enfin, cette étude des pingos a fait apercevoir la complexité des fluctuations du niveau marin dans cette partie ouest des îles Reine-Elisabeth. La mer se trouvait tout d'abord à un niveau supérieur au niveau actuel puisque des deltas anciens existent à une altitude voisine de + 10 m. Ces deltas se sont édifiés alors qu'une grande glaciation recouvrait au moins une partie de l'île, car près de la baie Satellite, ces deltas se raccordent à une plaine d'épandage glaciaire. Si notre interprétation est exacte, la mer est ensuite descendue sous le niveau marin actuel pour subir finalement une hausse l'amenant là où nous la trouvons maintenant. Le dernier mouvement de la mer aurait donc été, sur l'île Prince-Patrick, positif, soit opposé en sens à ce qui existe dans le reste des îles Reine-Elisabeth où les plages soulevées sont extrêmement apparentes. L'absence du soulèvement isostatique semble indiquer qu'une grande calotte glaciaire Wisconsin ne s'est pas étendue sur l'île Prince-Patrick au cours de cette dernière période froide.

REMERCIEMENTS

La présente étude a été réalisée grâce à une bourse de travail libre du Conseil des Arts, bourse qui nous a permis d'effectuer, pendant les étés 1965 et 1966, des recherches sur la morphologie périglaciaire de l'île Prince-Patrick. Nos travaux dans cette région ont été possibles grâce à l'accueil que nous avons reçu à la Direction de la géographie et à la Commission géologique du Ministère de l'Energie, des Mines et des Ressources. C'est l'Etude du plateau continental polaire qui nous a donné les moyens matériels de travailler dans l'Arctique en nous fournissant parmi d'autres services le ravitaillement et le support aérien.

Nous leur en sommes extrêmement reconnaissants et nous voulons spécialement remercier ici, MM. F. Roots, coordonnateur de l'Etude du plateau continental polaire et J. D. Ives, directeur de la Géographie, pour leur bienveillance.

Par ailleurs, MM. P. Macar, professeur à l'Université de Liège, A. Cailleux, professeur à la Sorbonne, J. G. Fyles, chef de la Section de la géologie du Pléistocene, de la Commission géologique du Canada, D. St-Onge du même organisme et W. S. B. Patterson de l'Etude du plateau continental polaire ont eu l'amabilité de relire et de critiquer le manuscrit. Leurs remarques ont permis d'améliorer notablement le texte originel. Nous les prions d'accepter nos remerciements.

BIBLIOGRAPHIE

Cailleux, A.
1964 : Genèse possible de dépôts chimiques par congélation. *Soc. Geol. Fr., Compte Rendu Sommaire des Séances*, numéro 1, 11-12.

Dylik, J.
1966 : Problems of ice wedge structures and frost fissure polygons. *Biuletyn Peryglacjalny*, numéro 15, 241-291.

Ek, C. et Pissart, A.
1965 : Dépôt de carbonate de calcium par congélation et teneur en bicarbonate des eaux résiduelles. *Acad. Sci. Paris, Comptes Rendus des Séances*, Tome 260, numéro 3, 929-932.

Fyles, J. G.
1965 : Surficial geology, western Queen Elizabeth Islands. Geol. Surv. Can., Report of Activities; field, 1964, Paper 65-1, 3-5.

Hamelin, L.-E. et Jacobsen, G.
1964 : Ile Melville (Canada arctique). Centre d'Etudes Nordiques, Travaux divers, numéro 5, Univ. Laval, Québec, 22 p.

Holmes, G. W., Hopkins, D. M. and Foster, H. L.
1963 : Pingos in central Alaska. Geol. Soc. Am., Special Paper 73, 173 p.

Leffingwell, E. de K.
1919 : The Canning river region, northern Alaska. U.S. Geol. Surv., Professional Paper 109, 251 p.

Lewis, C. R.
1962 : Icing mound on Sadlerochit river, Alaska. *Arctic*, v. 15, no. 2, 145-150.

Maarleveld, G. C.
1965 : Frost mounds: a summary of the literature of the past decade. *Mededelingen van de Geologische Stichting*, Nieuwe Serie no. 17, 3-16.

Mackay, J. Ross
1962 : Pingos of the pleistocene Mackenzie Delta area, *Geog. Bull.*, no. 18, 21-63.

Müller, F.
1959 : Beobachtungen über pingos. *Med. om Grønland*, Bd. 153, Nr. 3, 126 p.

Péwé, T. L.
1959 : Sand-wedge polygons – (Tesselations) in the McMurdo Sound region, Antarctica – a progress report. *Am. J. Sci.*, v. 257, no. 8, 545-552.

Pissart, A.
1965 : Les pingos des hautes Fagnes: les problèmes de leur genèse. *Annales Soc. Géol. Belg.* 88, 5-6, 277-289.
1966 : Le rôle géomorphologique du vent dans la région de Mould Bay (Ile Prince-Patrick, T. N-O., Canada). *Zeitschrift für Geomorphologie*, Band 10, Heft 3, 226-236.
1967 : Les polygones de tundra de l'île Prince-Patrick. A paraître dans les Mélanges de travaux géographiques offerts au professeur O. Tulippe à l'occasion de son éméritat – Liège.

Porsild, A. E.
1938 : Earth mounds in unglaciated Arctic northwestern America. *Geog. Rev.*, XXVIII, January, 46-58.

Shoumsky, P. A.
1955 : Principes de glaciologie structurale. Traduction par J. Pietresson de Saint-Aubin et A. Bauer dans *Annales* du Centre d'études et de documentation paléontologiques, numéro 22, 1957, 309 p.

Shumskii, P. A.*
1959 : Principles of geocryology (permafrost studies). Part 1, General geocryology – Chapter IX, Ground (subsurface) ice; 274-327. Technical translation 1130 by C. de Leuchtenberg, N.R.C. Can., 1964, 118 p.

Stager, J. K.
1956 : Progress report on the analysis of the characteristics and distribution of pingos east of the Mackenzie Delta. *Can. Geogr.*, no. 7, 13-20.

Tozer, E. T. and Thorsteinsson, R.
1964 : Western Queen Elizabeth Islands, Arctic Archipelago. Geol. Surv. Can., Mem. 332, 222 p.

*Shoumsky et Shumskii sont des façons différentes d'orthographier le même nom; le premier est une transposition en français, le second en anglais.

APPENDICE I

Moyennes mensuelles et moyenne annuelle de température (en degrés C.), et précipitations à Myggbukta (Est Groenland), Tuktoyaktuk (Delta du Mackenzie, Canada) et Mould Bay (Ile Prince-Patrick).
Les données de Myggbukta et de Tuktoyaktuk sont extraites de F. Müller, (1959); les valeurs de Mould Bay ont été calculées sur place d'après les archives de la station météorologique.

Janv.	Fév.	Mars	Avril	Mai	Juin	Juil.	Août	Sept.	Oct.	Nov.	Déc.	T° Moyenne annuelle	Précipitations annuelles en mm
Myggbukta (Groenland), 73°30′N., 21°30′W; (2 m above sea level): 1922–1937													
−20.0	−20.0	−21.6	−16.2	− 6.0	+ 1.4	+ 3.9	− 3.1	− 1.2	−10.4	−14.6	−17.9	−10.0	220
Tuktoyaktuk, (Mackenzie) Territoires du Nord-Ouest, 69°27′N, 133°2′W: 1948–1955													
−28.0	−31.2	−24.7	−17.2	− 5.7	+ 3.6	+10.5	+10.4	+ 3.6	− 6.9	−17.1	−26.1	−10.7	185
Mould Bay, Territoires du Nord-Ouest (île Prince-Patrick), 76°15′N, 119°21′W: 1948–1965													
−33.9	−36.0	−33.2	−23.8	−11.4	− 0.2	+ 3.3	+ 1.4	− 6.9	−17.3	−26.8	−31.4	−18°	81

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 218–231, 1967

THE INFLUENCE OF PLEISTOCENE CLIMATIC CHANGES ON THE DEVELOPMENT OF THE POLYGENETIC PEDIMENTS IN THE CYPRESS HILLS AREA, ALBERTA

*P. D. Jungerius**

ABSTRACT

The geomorphological history of the unglaciated pediments south of the Cypress Hills plateau is reflected in the materials covering their surface. Deposits and soils formed in an arid or semi-arid environment alternate with solifluction deposits and other periglacial features. The pediments are produced by a combination of pediplanation and cryoplanation.

RÉSUMÉ

L'histoire géomorphologique des pédiments non soumis à l'action des glaces au sud du plateau des collines Cyprès se réfléchit dans les matières qui recouvrent leur surface. Les sédiments et les sols, formés dans des milieux arides ou semi-arides, alternent avec les sédiments de solifluction et d'autres caractéristiques périglaciaires. Les pédiments résultent d'une combinaison de cryoplanation et de pédiplanation.

INTRODUCTION

The Cypress Hills in the southeastern corner of Alberta (Figure 1) form an irregular elongated plateau that slopes down from an elevation of 4,800 feet (1463 metres) at its western end, to 4,540 feet (1384 metres) at the Alberta-Saskatchewan border. Steep slopes separate the plateau from erosional surfaces that slope away toward the main drainage lines (Figure 2). These surfaces have been described as "pediment-like" features by Gravenor and Bayrock (1961) who thought that erosion took place under arid to semi-arid conditions.

In this paper the term "pediment" will be used in connection with these erosional surfaces, although they are not formed merely by the processes of an arid or semi-arid environment. Like their counterparts in the dry zone, they are rock-cut slopes of low gradient, veneered with a thin layer of loose debris and bordered by steep slopes. The aggradational lower section of footslopes usually found in dry regions is absent or poorly developed in the Cypress Hills area.

The pediments are underlain by soft rocks and appear to conform to the definition of *glacis d'erosion* proposed by Birot and Dresch (1966). However, the use of this term has not been adopted for this paper as the same term has been given various other meanings (*see* Dresch, 1957 p. 186).

MS submitted August, 1967. Revised March, 1968.

*Dr. P. D. Jungerius is a staff member of the Department of Physical Geography, University of Amsterdam. The field work for the present report was completed during the summers of 1966 and 1967 while he was temporarily on the staff of the Geographical Branch.

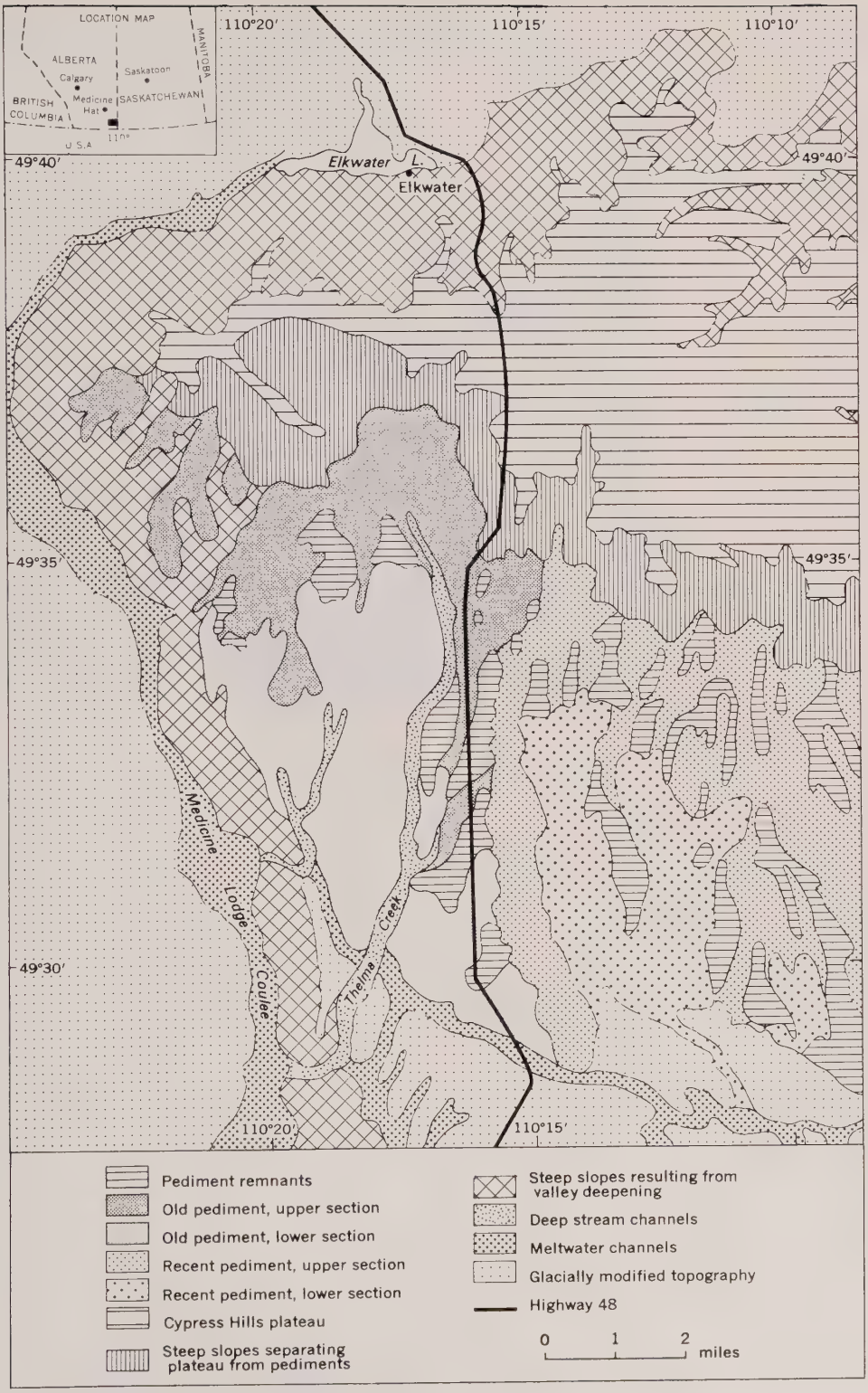


FIGURE 1. The Cypress Hills area of Alberta showing the plateau, the pediments and the drainage channels.

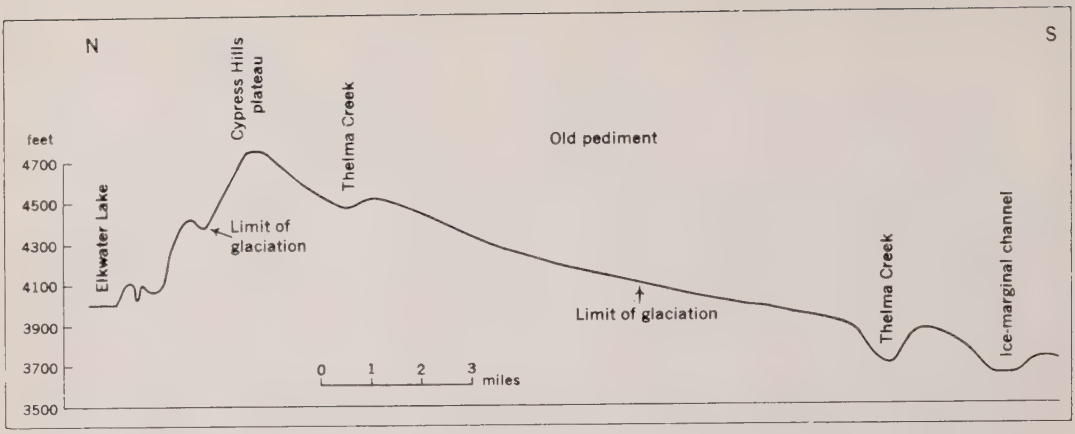


FIGURE 2. Section across Cypress Hills plateau and Pleistocene pediment south of Elkwater.

The Cypress Hills area was largely overrun by the Wisconsin glaciers, but the plateau and most of the southern pediments stood above the limit of glaciation (Westgate, 1964). These unglaciated areas were the object of geomorphological and pedological investigations carried out by the author during the summers of 1965, 1966 and 1967. Samples were analyzed in the Laboratory of Physical Geography and Soil Science, University of Amsterdam.

DESCRIPTION

The footslopes south of the Cypress Hills plateau may be divided into an old pediment where planative processes are largely inactive at present and a recent pediment. The surface of both pediments is irregular near the plateau as a result of stream incision. In many other respects they are very dissimilar. The recent pediment has been modified by lateral stream planation during the Holocene and has an undulating relief when traversed at right angles to the drainage system. The development of this pediment will be discussed in a later paper.

The old pediment, which was largely formed during the Pleistocene, becomes more and more flat away from the plateau. The main streams occupy deep channels but the incision of the smaller drainage lines is hardly discernible (Figure 3). All stream courses are dry for part of the year. The pediment surface drops from 4,450 feet (1356 metres) near the plateau to 3,875 feet (1181 metres) in the south. The Medicine Lodge Coulee, a meltwater channel according to Westgate (1964), forms the western boundary. South of the ice-marginal channels connected to the Medicine Lodge Coulee, the surface of the pediment was modified by ice.

Climate

The Cypress Hills experience a semi-arid climate, with one third of the annual rainfall occurring between June 1 and July 31. The mean annual precipitation is about 18 inches on the plateau, decreasing to less than 12 inches toward the south. Annual temperatures as recorded on the plateau average 36°F, with the maximum of about 60°F in July. For the surrounding plains, these figures range between 41°F and 69°F respectively. More detailed climatological data are given by McKay (1965).

Vegetation

The present natural vegetation consists of grass, with a marked change in the dominant species from the relatively humid north to the dry south (Wyatt *et al.*, 1941). Thickets occur along the valley fringes and forest covers the marginal slopes of the plateau.

Geology

The pediments cut across sediments of Upper Cretaceous to Tertiary age. The rocks have suffered little disturbance so that they maintain low dips (Williams and Dyer, 1930). The Bearpaw Formation underlying the lower

FIGURE 3
Shallow drainage line on flat surface of Pleistocene pediment.

section of the pediment consists of dark-coloured shales including, in the upper portion, several sandstone members. Most sediments lying above the Bearpaw Formation are poorly consolidated and should be referred to as sands, silts and clays (Furnival, 1950). The plateau is capped by the Cypress Hills Formation of Oligocene age, which consists of unconsolidated coarse conglomerate composed of rounded quartzite pebbles and cobbles averaging 2 to 3 inches in diameter.

Soils

The soils have developed in the thin veneer of surface materials covering the bedrock. They differ in profile characteristics due mainly to the varying climatic conditions under which they were formed (Wyatt *et al.*, 1941). They range from Dark Brown Chernozemic soils (National Soil Survey Committee of Canada, 1963) with a dark coloured *Ah* horizon in the area fringing the plateau, to Solonetzic soils showing a well-developed *Bn* horizon with a clayey texture and a columnar structure in the south. Most soils have a horizon of secondary calcium carbonate enrichment in the profile.

MATERIALS

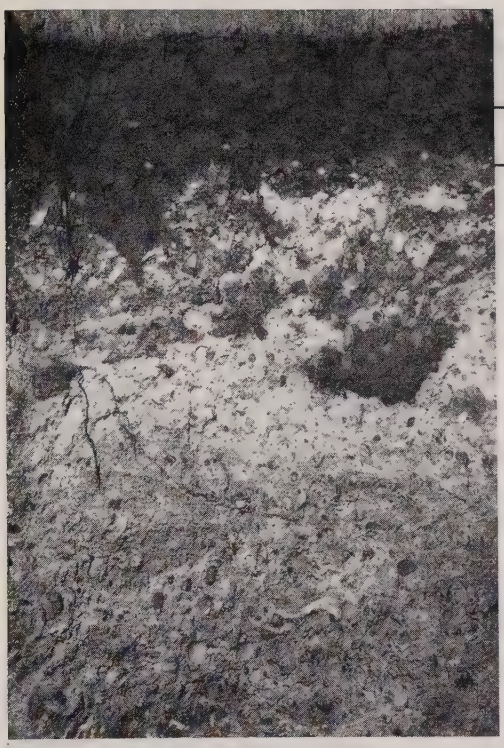
The loose materials covering the bedrock comprise preglacial (pre-Wisconsin) alluvium, periglacial solifluction material, and postglacial wash deposits and alluvium. The preglacial alluvium is only occasionally preserved in lower slope positions, but the solifluction material still covers large areas. It is invariably overlain by the Holocene wash deposits. Recent alluvium is restricted to the major stream beds. The most important types of material are present in the following section exposed in a gully near Medicine Lodge Coulee (Figure 4).

Exposed Section

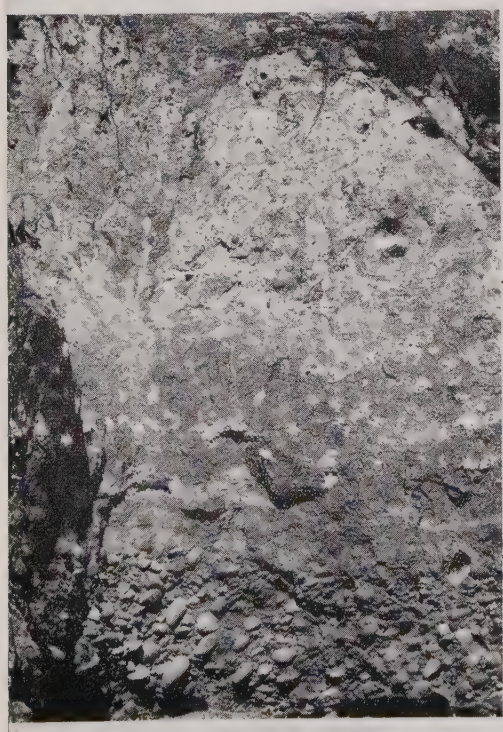
Location 49° 33′30″N, 110° 20′30″W
Slope 2°
Soil Dark Brown Solodic Soil (Atypical: no clear *AB* horizon)

Elevation 4,095 feet (1248 metres)
Vegetation grass

Parent Material	*Depth (cm)*	*Horizon*	*Description*
Wash deposits	0-39	*A2*	Dark yellowish brown (10YR4/4) loam; massive; hard; frequent rootlets; pH 6.1 (KCl 4.9); humus 3.4 per cent.
	39-47	*Bnt*	Yellowish brown (10YR5/4) clay loam; moderate medium columnar breaking easily to very hard angular blocky aggregates with dark brown (10YR4/3) coating; pH 6.6 (5.5); humus 1.5 per cent.
		(2Ah)	In other parts of the profile this position is occupied by a buried *Ah* horizon: very dark grey brown (10YR3/2) sandy clay loam; rare gravel; massive; hard; pH 6.0 (4.8); humus 5.0 per cent.
	47-76	*C*	Light olive brown (2.5Y5/3) clay loam; weak medium columnar breaking easily to very hard blocky aggregates with discontinuous dark surface staining; pH 8.0 (7.1).
Upper solifluction material (?)	76-103	*IICca*	Light olive grey (5Y6/2) sandy clay loam; many pebbles without preferred dip; very hard; pH 7.5 (6.6); humus 0.9 per cent; $CaCO_3$ 2.4 per cent; horizontal lower boundary.
Lower solifluction material	103-147	*III(A)C*	Pale olive (5Y6/3) silty clay loam; frequent pebbles; hard; pH 8.5 (7.6); humus 0.6 per cent; $CaCO_3$ 28.2 per cent; this horizon is very irregular and discontinuous; in upper part wedges filled with light olive grey (5Y6/2) sandy clay loam; few pebbles; pH 8.2 (7 3).
	147-248	*IIICk*	White (5Y8/1) clay loam; frequent pebbles; hard; pH 8.7 (8.0); $CaCO_3$ 55.1 per cent; in upper part involutions of *III(A)C* material, in lower part involutions of *IVCca* material.
Alluvial deposits	248-356	*IV(B)Cca*	Light yellowish brown (2.5Y6/4) sandy clay loam; hard; including strata of almost pure (92 per cent) $CaCO_3$ (caliche); pH 8.7 (7.5); $CaCO_3$ 21.1 per cent.
	356-445	*VC*	Light yellowish brown (2.5Y6/4) clay loam; abundant pebbles with low dip angle; pH 7.9 (6.9); no $CaCO_3$.
Bedrock (Bearpaw Formation)	445+	*VIC*	Dark grey sandy loam; stratified; no $CaCO_3$.



Upper section of profile



Lower section of profile

Preglacial alluvium

The stratified deposits below the solifluction layer were laid down directly on the rock-cut surface of the pediment. The coarse fragments in the pebble layer originate from the Cypress Hills Formation capping the plateau. They are embedded in a scarce sandy matrix derived from local bedrocks (Figure 5). The pebbles occur in predominant sub-horizontal position, 80 per cent having their maximum projection plane dipping at angles lower than 15 degrees. The size-frequency of the non-pebbly layer shows a maximum in the silt fraction which is higher than has been found in any of the bedrock samples analyzed so far and would appear to indicate aeolian influence (Figures 5 and 6). Wind-blown materials with a similar heavy mineral assemblage occur below the solifluction layer on the plateau. They are not derived from the same source as the aeolian materials in the superficial wash deposits which have a much higher green hornblende content (Table 1).

The succession of pebble and loam deposits is also found in the Holocene alluvium of the recent pediment, and is characteristic of the alluvial veneer on pediments developed in dry climates (Coque, 1962). Arid conditions are also indicated by the presence of caliche in the alluvial loam where it forms discontinuous, sub-horizontal layers of almost pure calcium carbonate interbedded with calcareous sandy clay loam. The profile morphology suggests secondary carbonate enrichment in an existing soil, as occurs on a more reduced scale in present soils.

According to Coque, the climate favourable to caliche formation should be sufficiently humid to permit the growth of vegetation necessary for the supply of carbon dioxide, but with a pronounced dry season to allow the concentration of $CaCO_3$ in the sub-soil. For the formation of caliche in the southwestern United States and North Africa, Arellano (1953) sug-

FIGURE 4
The superficial deposits covering the Pleistocene pediment.
I Wash deposits
II Upper solifluction material (?)
III Lower solifluction material with congeliturbate structures
IV Alluvial loam with caliche
V Alluvial pebble deposit

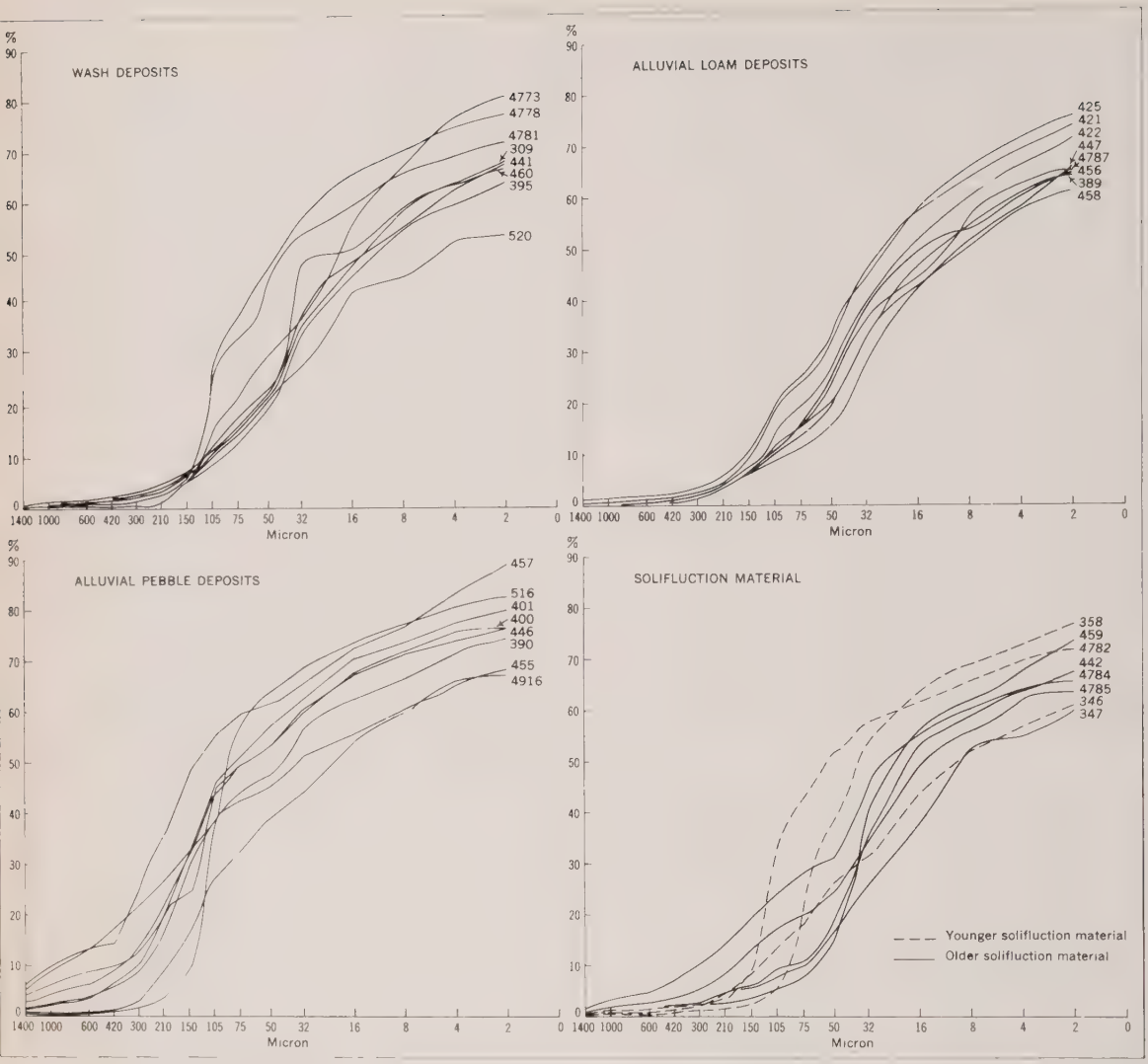


FIGURE 5. Grain-size distribution of the smaller than 2 mm fraction in the deposits covering the unglaciated pediments. The samples Nos. 4778 to 4787 and No. 4916 are taken from the profile described in this paper.

gested an average annual rainfall between 25 and 60 cm, and an average temperature falling below 32°F for at least one month. The latter condition is not fulfilled in North Africa, but may well have applied to the Cypress Hills pediments. Soil colours are similar to those in present soils and lack the reddish hues indicative of a prolonged hot season.

Solifluction material

Most profiles outside the stream beds show the presence of an unsorted and unbedded deposit containing pebbles derived from the Cypress Hills Formation on the plateau, without preferred dip and embedded in an abundant matrix of calcium carbonate, silt and clay. The matrix constitutes generally more than 40 per cent of the volume weight, and unless decalcified by later pedogenic processes, contains up to about 50 per cent $CaCO_3$.

By these features this sediment is easily distinguished from sediments laid down in this area by water, wind or ice. Pebbles are scarce or absent in wind-borne wash and fine-grained alluvial deposits, while those in coarse alluvium have a preferred sub-horizontal position and

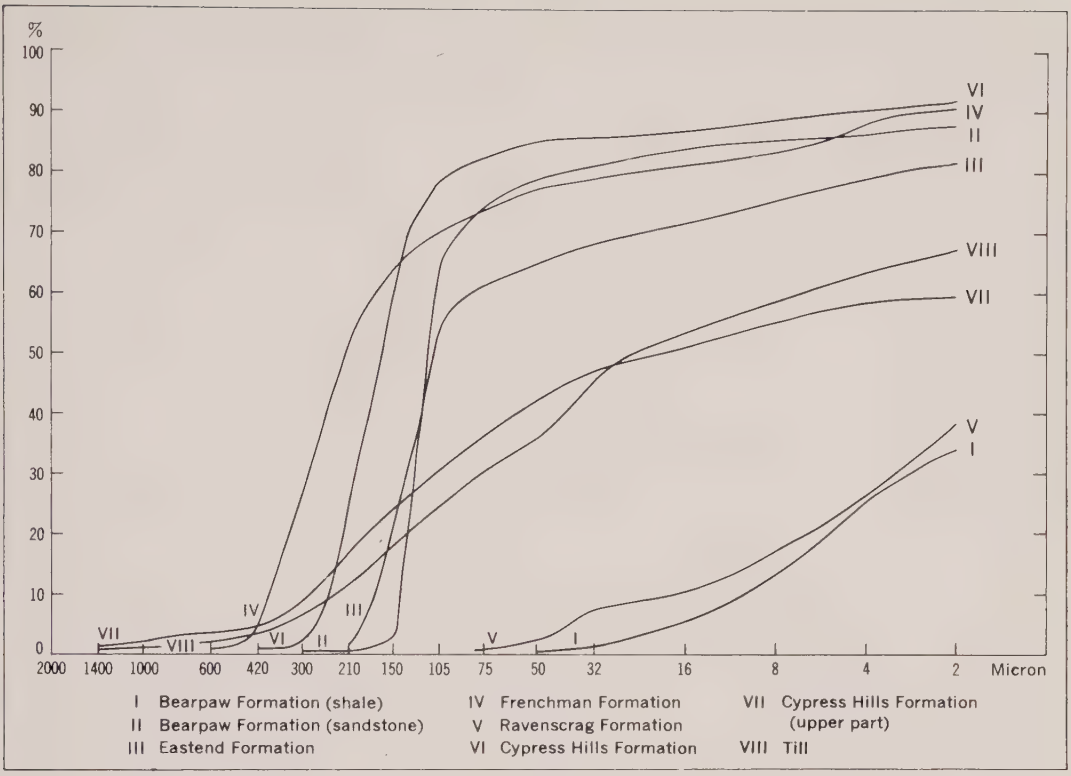


FIGURE 6. Grain-size distribution of the smaller than 2 mm fraction in local bedrocks and till.

I	Bearpaw Formation (shales)	V	Ravenscrag Formation
II	Bearpaw Formation (sandstone)	VI	Cypress Hills Formation
III	Eastend Formation	VII	Cypress Hills Formation (surface)
IV	Frenchman Formation	VIII	Till

are closely packed in a sandy matrix poor in calcium carbonate. The matrix of coarse alluvium occupies no more than about 20 per cent of the total volume weight. Where coarse alluvium was subject to periglacial processes, the pebbles are deranged but the matrix maintains its fluvial character.

Till in the surrounding areas exhibits similar textural heterogeneity and scattered occurrence of coarse debris, but differs in many other characteristics. Pebbles other than those derived from the Cypress Hills Formation are present among the erratics, and the matrix has a much lower $CaCO_3$ and silt content. Moreover, green hornblende which attains values of 50 per cent or more in the heavy fraction of till samples so far analyzed, comprises no more than 10 to 25 per cent in the material here discussed. In the glaciated area south of the ice-marginal channels, this material was pushed into a hummocky relief, but this process was accompanied by admixture with erratics of northern origin and by a change in the grain-size distribution of the matrix.

The material extends as a featureless spread over much of the pediment surface but tends to thicken in a down-slope direction. Areal extent and lithology are evidence for mass-movement under gravitational influence. Of the many types of mass-movement occurring in nature (Sharpe, 1938), only solifluction produces material with the properties found here. In fact, all ten criteria proposed by Büdel (1959) for classifying slope waste as solifluction material, are fulfilled:

– The thickness varies from practically nil in upper slope positions where erosion was active, to approximately 150 cm in some de-

Table 1

Heavy mineral composition in percentages of the fraction 30-500 micron, in the deposits covering the Pleistocene pediment, and in other local materials

Horizon	Depth in cm	Material	Not determined: opaque	Not determined: others	Zircon	Tourmaline	Rutile	Anatase	Sphene	Chloritoid	Staurolite	Garnet	Kyanite	Sillimanite	Andalusite	Epidote group	Hornblende green	Hornblende greenish brown	Hornblende brown	Tremolite	Glaucophane	Hypersthene	Augite
2Ah	39–47	Wash deposits	40	27	7	6	2	5	16			16			4	24	15	3	1			1	
C	47–76	Wash deposits	23	20	13	5	3	9	6			10			2	34	16			1			1
IICca	76–103	Upper solifluction material	35	40	8	7	2	3	14			18				27	20			1			
III(A)C	103–147	Lower solifluction material	31	13	22	3	7	10	1	1		11	1			29	12			2		1	
IIICk	147–248	Lower solifluction material	34	23	21	6	3	6	6			15			2	19	7	6	6				3
IV(B)Cca	248–356	Alluvial deposits	28	40	28	6	8	6	7			8			1	19	3	13	1				
VC	356–445	Alluvial deposits	19	7	17	3	3	4				4			1	8	3	56				1	
		Upper aeolian deposit, Cypress Hills Plateau	19	18	10	1	5	6	2		1	11				18	39		2			1	4
		Lower aeolian deposit, Cypress Hills Plateau	22	16	36	4	5	10	10			9		1		19	5	1					
		Till	14	9	6		1	2			1	10		1		18	56		1			3	1
		Cypress Hills Formation	46	23	12	5	2	1	1			13	1			60	4			1			
		Ravenscrag Formation	28	27	36	26	10	16	7			1			1	2			1				
		Frenchman Formation	14	20	17	14	1	7				16			4	39	1						1
		Eastend Formation	12	35	17	7	4	2	11			18			5	36							
		Bearpaw Formation	18	48	13	13	6	4	22			24			7	10					1		

pressions, thus remaining well below the maximum of 2 to 4 metres set by Büdel.

– Movement occurred on slopes of very low gradient, in some instances probably not much more than the present surface slope of about 1 degree.

– Sorting is poor, and the pebbles are scattered randomly throughout a matrix which often forms the bulk of the mass. Only near the surface in some places has sorting resulted in the formation of stone polygons, but they represent the final stages of the periglacial period when the material was already largely immobile.

– The deposit is essentially unbedded.

– Frost-scattered pebbles are present, though in small quantities due to the poor susceptibility of the quartzite pebbles to congelifraction.

– Congeliturbate and solifluidal structures have been formed in the material as well as below the contact with the underlying sediments.

– The material had wide-spread occurrence, and extensive remnants still cover most of the plateau and the older sections of the pediments.

– Transport of the material over appreciable distances is indicated by the presence of pebbles derived from the Cypress Hills Formation covering the plateau adjacent to the pediments.

– The mass-movement took place during the Pleistocene as is shown by the periglacial features in the underlying strata and by periglacial surface modifications. The latter comprise frost wedges, congeliturbate structures and stone polygons. The involutions in the upper part of the deposit shown in Figure 4 has been interpreted as mechanical mixing (congeliturbation) of incompletely decalcified upper horizons of an arctic soil (Hill and Tedrow, 1961).

– The material is stable under present-day conditions as is evidenced by undisturbed fossil and recent soils developed in the overlying Holocene wash deposits.

The many cryogenic features in and below the deposit suggest that movement took place under permafrost conditions, and the term

solifluction here used is synonymous with congelifluction (Dylick, 1957) and geli-solifluction (Czajka, 1958). Literature on solifluction is extensive and only a few relevant studies will be discussed in this paper.

In spite of their common origin, solifluction (congelifluction) deposits show many different features. According to Büdel, these differences are to a large extent due to the effects of climate. In Canada as in Europe, a distinction should be made between the present arctic environment and the fossil periglacial environment at lower latitudes (Büdel, 1959). In the latter, the incoming solar radiation was higher and this affected the melting of the snow, the depth of the active layer, and the desiccation of the soil profile during the summer months. Moreover, much loose debris was available at lower latitudes from previous interglacial periods when chemical weathering and soil formation was active. Büdel attached much importance to the presence of clay, but the admixture with aeolian silt also promoted slope instability. Initial loess deposits are therefore almost always disturbed by solifluction (Louis, 1961), a feature also observed on the Cypress Hills plateau (Jungerius, 1966). St-Onge (1965) emphasized the role of silt in mass-movements observed in the Northwest Territories. Both clay and silt are abundantly present in the solifluction deposits in the Cypress Hills area.

The differences observed led Büdel to distinguish between periodic and episodic solifluction. Periodic solifluction prevails in arctic and high altitude zones and is characterized by steep slopes, shallow penetration of summer thaw, a certain degree of stratification parallel to the slope, and preferred orientation of the coarse debris. The periglacial mass-movements in the Cypress Hills area should be classified as episodic solifluction which is the normal type in fossil periglacial zones. As a flow movement active on slopes of very low gradient, it must contain clay and other fine-grained elements to overcome internal friction. Characteristic for this type of solifluction is the presence of congeliturbate structures, sometimes at appreciable depth.

A distinct feature of the solifluction material in the Cypress Hills area is the absence of preferred inclination shown by the coarse particles. From dip measurements carried out in four exposures it appeared that more than 70 per cent of the pebbles have their maximum projection plane dipping at angles exceeding 15 degrees. Maxima are poorly expressed and apparently insignificant. Azimuth measurements were omitted as they could not be compared with the direction of movement which is uncertain on the very gentle slopes.

Reports on fabric studies of solifluction material involving dip measurements are few (Johansson, 1965) but appear to support the observations made in the Cypress Hills. Lundqvist gives a possible explanation: "In the initial area of the solifluction the boulders lie relatively irregular. After that they begin to align themselves in the direction of flow, and at the same time they rotate so that their up-flow part is lifted up, until the boulders stand vertically. The cause must be that the surface layer, owing to its greater movability – less friction – moves more easily . . ." (Lundqvist, 1948, p. 9, translated by Johansson, 1965). A similar arrangement of stones in solifluction material has been reported by Smith (1956) for an area on Spitsbergen underlain, like the Cypress Hills pediments, by nearly horizontal beds of soft rocks comprising sandstones, mudstones and shales.

Frost heaving may also produce steep inclination of coarse particles, but according to Lundqvist (1949) this process is always accompanied by sorting: the largest boulders lie uppermost and from there the size decreases downwards. No such sorting has been observed in the main mass of the solifluction material of the Cypress Hills pediment and frost heaving has produced no more than an occasional stone polygon.

Some sections display a second mass-movement layer with pebbles, laid down before the Holocene slope wash, and separated from the underlying solifluction material by non-pebbly loam which fills up the frost wedges in the discussed section (Figure 4). The pebble distribution is similar to that in the solifluction material, but the pebbles themselves are somewhat smaller and are embedded in a more sandy and less calcareous matrix.

A few stone polygons have been found outside the limits of the plateau and the pediments, but otherwise, periglacial features are

scarce in the glaciated areas. This may be due to climatic differences as the present increase in precipitation with altitude may also have existed when periglacial conditions prevailed, favouring soil mobility in the higher parts. Relative stability of the slopes in the till plains could also result from lower clay and silt content of the soil materials. Another factor, however, may be as or even more important. From the glacial reworking of the solifluction material covering the foot of the pediments it may be inferred that solifluction began before the arrival of the Wisconsin glaciers. This is supported by Brunnschweiler's statement that the permafrost was already in existence when the Wisconsin ice reached its southernmost position in the Midwest of the United States (Brunnschweiler, 1962). Thus, periglacial features in the Cypress Hills could have persisted in the area above the ice, but were elsewhere overridden by the glaciers. Permafrost conditions could not be restored or at least only incompletely restored, in the time of climatic amelioration when the ice receded.

Wash deposits

The Holocene slope wash processes covered the solifluction deposits on most slopes with a loamy layer that in places may reach a thickness of 50 cm. The grain-size frequency of this material is similar to that of loamy alluvial strata. The mode of origin is not fully understood. The high green hornblende content indicates aeolian influence (Table 1) and Westgate (1965, p. 99) included these deposits with the Pleistocene "loess" covering the plateau. However, Holocene palaeosols buried in this material indicate a more recent age. It is assumed that they are reworked aeolian materials mixed with local pebbles and sand, laid down by unconcentrated slope wash (sheet wash). Any possible stratification has been destroyed by soil-forming processes.

Conditions favourable for these slope-wasting processes prevailed more than once during the Holocene. They were interrupted by a sufficiently long period to allow the formation of a grassland soil, the buried remnants of which have been found in many wash deposits. Radiocarbon dates show that this soil was formed approximately 4,000 years ago. Like the present, it was a time of increased vegetal cover and slope stability, and absence of slope wash. The effects of the alternating phases of landscape stability and instability on the geomorphology of the Cypress Hills pediments will be discussed in more detail in a later paper.

DISCUSSION

Superficial deposits and slopes show that two groups of processes must be considered in connection with pediment formation in the Cypress Hills area. The initial form resulted from processes active in an arid or semi-arid environment, but was later modified by periglacial processes. Both groups of processes have been abundantly described in the literature and will not be discussed here, but it is pertinent to point out that the land forms they produce are similar in the juxtaposition of steep and smooth slopes with sharp breaks in between.

From the resemblance of the alluvial deposits below and above the solifluction material it would seem that the preglacial (pre-Wisconsin) climatic conditions were not unlike those prevailing today, although the absence of caliche in the Holocene soils indicates that they were not identical. There is little doubt that sheet wash contributed to the development of the recent pediment, but a more important role was played by the streams issuing from the plateau and flowing down the pediment. They display a strong tendency to lateral erosion, removing the weak rocks exposed in the stream banks while the pebble-protected stream bed remains relatively unaffected. This process produced a characteristic pattern of elongated pediment remnants stretching out down-slope (Figure 1). The occurrence of a similar pattern on the Pleistocene pediment suggests that at one time the development of both pediments ran parallel.

Lateral stream erosion leaves a pediment with an irregular, undulating relief when traversed at right angles to the direction of stream flow, and it is perhaps not too much to assume that, before the glaciers arrived, the surface of the Pleistocene pediment resembled that of the recent pediment as it is today. If a similar comparison may be made regarding the steep slopes separating the Pleistocene pediment from the Cypress Hills plateau, it must be assumed that they receded under the influence

of processes involving erosion by runoff, undercutting by lateral planation, and linear erosion – leaving a scarp that may have been even more indented than it is at present.

The onset of periglacial conditions led to a marked change in the erosive processes operating on the plateau. In protected places the preglacial soil was disturbed by frost action but remained in place. Elsewhere much material was removed by solifluction. By lowering the interfluves and filling the valleys, cryoplanative processes erased the irregularities left by the streams in the previous period, ultimately producing a topography that, on the lower section of this pediment, is almost flat. The steep slopes separating the pediment from the plateau retreated farther by landslide phenomena for which conditions were particularly favourable during late-glacial times (Thorarinsson *et al.*, 1959; Rapp, 1960). Their present stability is demonstrated by the presence of undisrupted alluvial fans cutting across the slides, with buried soils in the surface layers that are about 4,000 years old.

Thus, the periglacial processes supplemented the effect of previous arid or semi-arid processes, and accentuated the juxtaposition of smooth and steep slopes. The resemblance of the arid and the periglacial morphogenetic system has been pointed out by various authors (Dylick, 1957, St-Onge, 1965). Both systems promote the development of pediments and pediment-like features, and it is not surprising that these forms are particularly well presented in the Cypress Hills area where dry and periglacial climates alternated.

AGE

Alden (1932) correlated the top of the Cypress Hills plateau with similar features in Montana into a surface of wide extent, the *Cypress Plain,* for which he suggested an Oligocene-Miocene age. Gravel-capped erosion remnants below the level of the Cypress Plain in Montana were included in the Flaxville Plain which was, according to Alden, completed in Pliocene time. Lower terraces were classified as No. 2 and No. 3 benches and were assigned to the Pleistocene.

Williams and Dyer (1930) interpreted the pediments bordering the Cypress Hills plateau as "remnants of an old land surface entrenched below the Cypress Plain" and correlated these forms with the Flaxville Plain. Broscoe (1965), basing his studies on aerial photographs and literature, mapped a number of pediment remnants and part of the Pleistocene pediment as Flaxville Plain, and the remaining parts of the pediments as No. 2 and No. 3 benches. However, correlation of such features over long distances have to be handled with care. Alden himself (1932, p. 13) described the pediments of the Cypress Hills as "a new and lower set of valley plains that slopes gently to the main streams," but refrained from correlating these features with erosion levels in Montana.

The pediment here discussed has been dated by correlation with the drift sheets that were mapped by Westgate (1965). During the time of maximum glaciation the ice covered a large part of the southern pediments reaching an elevation of 4,050 feet (1235 metres). This glacier deposited the Elkwater drift which is of pre-*classical* Wisconsin age (Westgate, 1965). The surface of the Elkwater drift became fully integrated into the pediment surface in the time that followed, and when the Wild Horse glacier entered the Cypress Hills area periglacial mass-movements had smoothed off the lower section of this pediment to its present flat relief. This pediment is therefore contemporaneous with the Wild Horse glaciation which Westgate believed to be of *classical* Wisconsin age.

The calcareous soil in the alluvial deposits underlying the solifluction material shows no signs of degradation and it is therefore assumed that the time the arid climate responsible for its formation prevailed, immediately preceded the Wild Horse glaciation. Interglacial, rather than pre-Pleistocene, conditions are also indicated by the presence in these alluvial deposits of silt assumedly of aeolian origin. The relative youth of this pediment, as indicated by the superficial deposits, is in accord with the character of the underlying Upper-Cretaceous and Tertiary sediments. It is unlikely that Tertiary surfaces would be preserved for any length of time in materials so easily erodable as the unconsolidated bedrocks over which the pediment is formed.

Holocene modifications to the surface of the Pleistocene pediment were relatively insignificant, comprising mainly the deposition of a

thin sheet of wash materials. Lateral stream erosion which contributed so much to the development of the recent pediment is of little importance here. This is due to a number of reasons, the most important of which are the considerable incision of the main streams to adjust to the lower level of the Medicine Lodge Coulee and the ice-marginal channels which also lowered the ground-water level; the small supply of pebbles from the plateau which has been reduced to a mere ridge; and the forest covering the southern flanks of the plateau, preventing rapid runoff.

ACKNOWLEDGMENTS

The research reported here was carried out under a contract with the Geographical Branch, Department of Energy, Mines and Resources.

The samples were analyzed in the Laboratory of Physical Geography and Soil Science, University of Amsterdam, through the courtesy of Professor Dr. J. P. Bakker and Dr. H. J. Müller. Valuable assistance during the field work was received from Mr. B. Laing, Mr. P. L. Puxley, and Mr. T. Sookocheff.

REFERENCES

Alden, W. C.
1932 : Physiography and glacial geology of eastern Montana and adjacent area. U.S. Geol. Surv., Prof. Paper 174, 133 p.

Arellano, A. R. V.
1953 : Barrilaco pedocal, a stratigraphic marker ca 5,000 B.C. and its climatic significance. C.R. XIX Congr. geol. int., Alger, 1952, fasc. 7, pp. 53-76.

Birot, P. and Dresch, J.
1966 : Pediments et glacis dans l'Ouest des Etats-Unis. Ann. de Geogr. 411, pp. 513-552.

Broscoe, A. J.
1965 : The geomorphology of the Cypress Hills-Milk River Canyon area, Alberta. Alta Soc. Petr. Geol., 15th Ann. Field Conf. Guidebook, pt 1, pp. 74-84.

Brunnschweiler, D.
1962 : The periglacial realm in North America during the Wisconsin Glaciation. Biuletyn Peryglacjalny 11, pp. 15-27.

Büdel, J.
1959 : Periodische und episodische Solifluktion im Rahmen der klimatischen Solifluktionstypen. Erdkunde 13, 4, pp. 297-314.

Coque, R.
1962 : *La Tunisie Presaharienne.* Colin, Paris, 476 p.

Czajka, W.
1958 : Lage- und Materialbestimmtheit von Frostmusterböden. Kinzl-Festschrift, Schlern-Schriften 190, Innsbrück.

Dresch, J.
1957 : Pediments et glacis d'erosion, pediplains et inselbergs. L'Information Geogr. 21, pp. 183-196.

Dylick, J.
1957 : Tentative comparison of planation surfaces occurring under warm and cold semi-arid climatic conditions. Biuletyn Peryglacjalny 5, pp. 175-186.

Furnival, G. M.
1950 : Cypress Lake map area, Saskatchewan. Geol. Surv. Canada, Mem. 242, 161 p.

Gravenor, C. P. and Bayrock, L. A.
1961 : Glacial deposits of Alberta. Soils in Canada. Roy. Soc. Canada, Spec. Publ. 3, pp. 33-50.

Hill, D. E. and Tedrow, J. C. F.
1961 : Weathering and soil formation in the arctic environment. Am. J. Sci. 259, pp. 84-101.

Johansson, C. E.
1965 : Structural studies of sedimentary deposits. Geol. Fören. Stockholm Förh. 87, pp. 3-61.

Jungerius, P. D.
1966 : Age and origin of the Cypress Hills Plateau surface in Alberta. *Geog. Bull.* v. 8, no. 4, pp. 307-318.

Louis, H.
1961 : *Allgemeine Geomorphologie.* Berlin, 355 p.

Lundqvist, G.
1948 : Blockens orientering i olika jordarter. Sveriges Geol. Unders. C, 497, pp. 1-29.

1949 : The orientation of the block material in certain species of flow earth. Geogr. Ann. 1-2, pp. 335-347.

McKay, G. A.
1965 : Climatic maps of the Prairie Provinces for agriculture. Climat. Studies 1, Dept. of Transport, Meteor. Branch, Toronto.

National Soil Survey Committee of Canada
1963 : Report on the fifth meeting of the Nat. Soil Surv. Comm. held at Winnipeg, Manitoba, 92 p.

Rapp, A.
1960 : Recent development of mountain slopes in Kärkevagge and surroundings, Northern Scandinavia. Geogr. Ann. 42, 2-3, pp. 73-200.

Smith, J.
1956 : Some moving soils in Spitsbergen. J. Soil Sci. 7, 1, pp. 10-21.

Sharpe, C. F. S.
1938 : Landslides and related phenomena. Columbia University Press, New York, N.Y., 137 p.

St-Onge, D.
1965 : La géomorphologie de l'Ile Ellef Ringnes, Territoires du Nord-Ouest, Canada. Etude Geogr. 38, Geogr. Branch, Ottawa, 46 p.

Thorarinsson, S., Einarsson, T., and Kjartansson, G.
1959 : On the geology and geomorphology of Iceland. Geogr. Ann. 41, 2-3, pp. 135-169.

Westgate, J. A.
1964 : The surficial geology of the Foremost-Cypress Hills area, Alberta, Canada. Unpubl. Ph.D thesis, Univ. of Alberta, 208 p.
1965 : The Pleistocene stratigraphy of the Foremost-Cypress Hills area, Alberta. Alta. Soc. Petr. Geol., 15th Ann. Field Conf. Guidebook pt. 1, pp. 85-111.

Williams, M. Y. and Dyer, W. S.
1930 : Geology of southern Alberta and southwestern Saskatchewan. Geol. Surv. Canada, Mem. 163, 160 p.

Wyatt, F. A., Newton, J. D., Bowser, W. E. and Odynsky, W.
1941 : Soil survey of Milk River sheet. Univ. of Alberta, Coll. Agric. Bull., 36, 105 p.

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 232-261, 1967

HYDROLOGY OF THE LEWIS GLACIER, NORTH-CENTRAL BAFFIN ISLAND, N.W.T., AND DISCUSSION OF RELIABILITY OF THE MEASUREMENTS

*Anonymous**

ABSTRACT

The Lewis Glacier is the only outlet glacier of the Barnes Ice Cap. Its surface area is 182 km^2 and the snout lies at an elevation of 245 metres, much below the general ice cap margin. The 1964 net budget was -65.4×10^6 m^3 water equivalent, representing a specific net loss over the entire glacier surface of 35.7 cm water equivalent. The 1965 net budget was -92.5×10^6 m^3 water equivalent, a specific net loss of 50.7 cm. A standard error margin of ± 12 per cent is indicated for the net budget.

Water budgets were computed for the seasons 1963 to 1965 for the Lewis River watershed, of which the glacier comprises 88.8 per cent. Error analysis showed that maximum discrepancies as great as $+67$ per cent or -21 per cent of runoff might have occurred from the data, but that the actually sustained discrepancies were less than ± 10 per cent. Reasonable values of glacier net budget can be estimated from water budget accounts. On this basis a net budget of -126×10^6 m^3 water equivalent is estimated for 1963.

The *sensitivity* of the watershed to available heat, expressed as degree-hours, is used to account for the behaviour of runoff as the season progresses and melting proceeds on the glacier, thereby relating runoff to weather conditions. The 1963 season was a warm one dominated by glacier melt, so that a regular runoff hydrograph resulted, whereas 1964 and 1965 were cool seasons whose runoff was characterized by storm peaks and little seasonal trend.

RÉSUMÉ

Le glacier Lewis est le seul glacier de décharge de la calotte glaciaire Barnes. Sa superficie est de 182 km carrés et son front, situé à une altitude de 245 mètres, se trouve bien au-dessous de la bordure de la calotte glaciaire. Le bilan net pour l'année 1964 a été l'équivalent en eau de -65.4×10^6 m^3, ce qui représente une perte nette spécifique, pour l'entière superficie du glacier, de 35.7 cm d'équivalent en eau. Le bilan net pour l'année 1965 a été de -92.5×10^6 m^3 en équivalent d'eau, soit une perte spécifique de 50.7 cm. On indique une marge d'erreur moyenne de $\pm$ 12 p. 100 pour les bilans nets.

Pour ce qui est du bassin hydrographique de la rivière Lewis dont le glacier représente 88.8 p. 100, les bilans hydriques ont été calculés pour les saisons allant de 1963 à 1965. Un calcul d'erreur a montré qu'il pourrait exister des écarts maximums de $+67$ p. 100 à -21 p. 100 par rapport à l'écoulement déterminé par les données, mais que les écarts réellement subis étaient inférieurs à $\pm$ 10 p. 100. Des valeurs raisonnables de bilan net de glacier peuvent être

MS submitted August, 1967.

*This paper, originally prepared as an internal memorandum giving a critical evaluation of the results obtained and the methods employed in the Lewis Glacier research project, was later revised, modified and extended by various members of the Glaciological Section of the Geographical Branch.

établies à l'aide des statistiques de bilans hydriques. Partant de ce principe, le bilan net de l'année 1963 a été évalué à -126×10^6 m^3 en équivalent d'eau.

La «sensitivité» du bassin hydrographique à la chaleur en disponibilité, exprimée en heures-degrés, peut servir à expliquer le comportement de l'écoulement à mesure que la saison avance et que la fonte agit sur le glacier. L'établissement du rapport entre l'écoulement et les conditions atmosphériques dépend aussi de cette «sensitivité». La saison de 1963 a été chaude et dominée par la fonte du glacier; elle a entraîné un régime d'écoulement continu. Les saisons de 1964 et 1965, pour leur part, ont été fraîches, et leur écoulement, caractérisé par des apogées dus à des tempêtes et à la quasi-absence de tendance saisonnière.

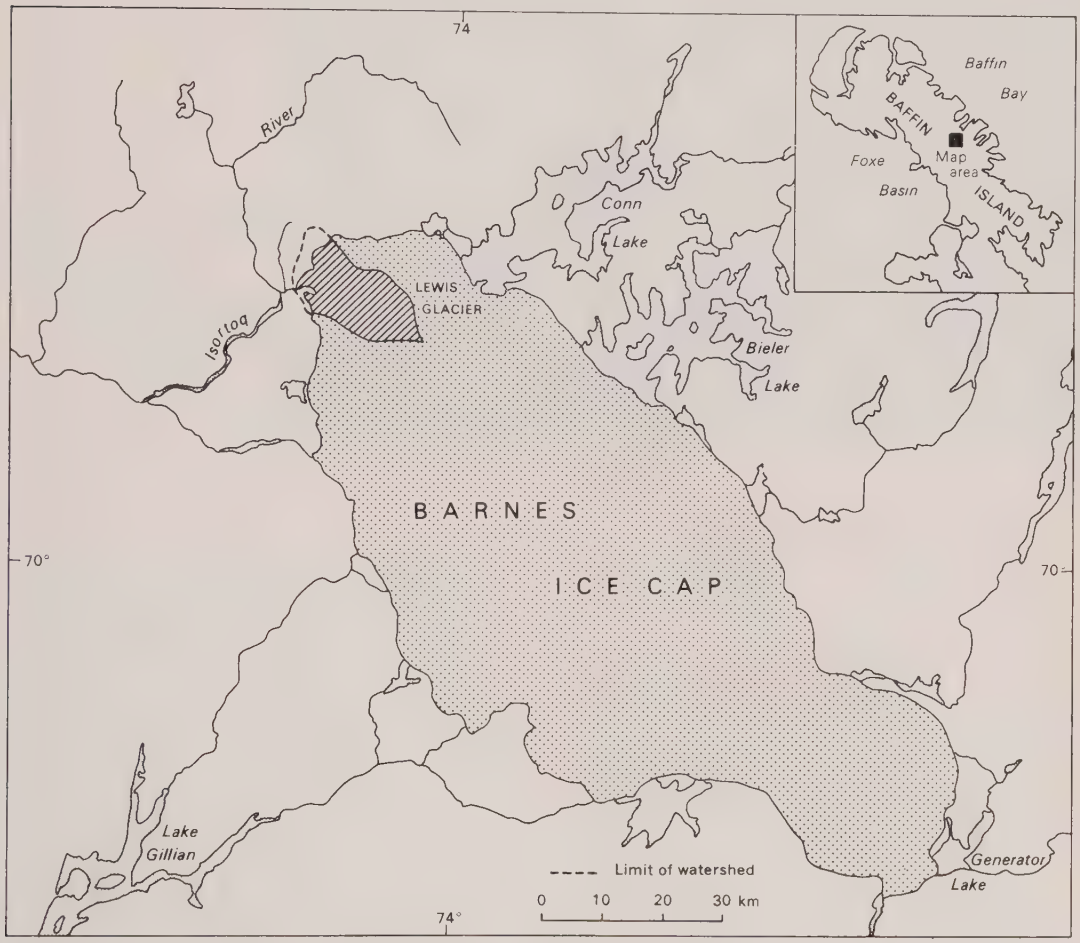


FIGURE 1. North-central Baffin Island showing the location of the Barnes Ice Cap and the Lewis Glacier. The dotted line northwest of the glacier snout marks the limits of the watershed.

INTRODUCTION

The Lewis Glacier, a small outlet glacier of the Barnes Ice Cap in north central Baffin Island is situated at 70°24′N, 74°53′W, (Figure 1). It occupies a major valley straddled by the northwestern corner of the Ice Cap (Figure 2). It brings the ice margin down to 245 metres above sea level, the lowest elevation found anywhere around the perimeter of the entire Ice Cap. The general elevation of the

FIGURE 2
Aerial view of the Lewis Glacier snout looking up-glacier toward the Barnes Ice Cap and showing, left centre, the ice cliffs bordering the Lewis River and, upper right, The Triangle glacier.

margin at the north end of the Barnes Ice Cap lies at about 500 metres. The glacier shows no sign of present movement, and the snout is melting back relatively rapidly.

The Lewis Glacier has an area of 182 km^2. It rises from an elevation of 245 metres to 965 metres, though most of its area lies above 500 metres (Figure 3).

Glaciological and hydrological observations on the glacier commenced in late June 1963, as part of the Geographical Branch investigations of mass balance of the northern portion of the Barnes Ice Cap and the history of deglaciation in the adjacent area. A partial water budget was compiled for 1963, but 1964 was the first complete budget year for which data were obtained. The present paper reports the results of investigations to the end of the 1965 budget year.

Two methods of mass balance accounting have been employed on the Lewis Glacier:

– glacier mass budget was computed by direct measurements of accumulation and ablation on the ice;

– a water budget was compiled on the basis of stream discharge measurements for the Lewis River drainage basin, of which the glacier forms the major part. An attempt was made to isolate the contribution of the glacier to the total water budget.

An analysis of possible errors in the data accompanies this report. With increasing use of glacier mass balance studies as a part of water resource inventories and as a basis upon which to build further investigations of glacier behaviour, it becomes very important to know how accurate the results may be. Rather serious limitations occur in the data of the present study and as a result some portions of the analysis have been pushed beyond the strict limits of statistical permission. The results must not therefore be interpreted closely, but only in terms of what they may indicate for the relative reliability of the various observations. It often happens that glaciological data is woefully incomplete, but researchers may be sure of improving studies only if they can clearly identify those aspects of the work for which pre-

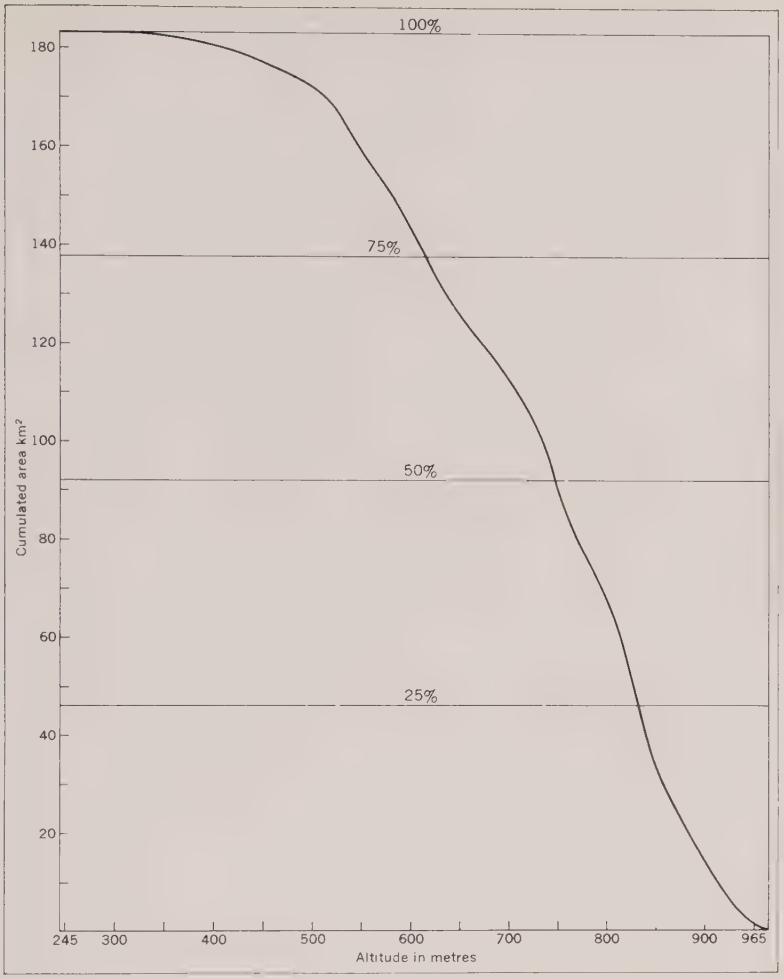


FIGURE 3
Hypsometric curve of the Lewis Glacier.

cision can be improved with reasonable effort. This discussion of errors is therefore presented in the hope of providing a guide for the planning of efficient observation programs in future research studies of this nature.

Part I

MASS BUDGET MEASUREMENTS ON THE LEWIS GLACIER

Glacier mass budget measurements were made according to the methods described by Østrem (1964), though some modifications were made for work on an arctic glacier.

The area of the glacier was defined by the surface meltstream watershed, which can be accurately outlined from RCAF 1961 vertical aerial photography: it totalled 182.4 km^2 (result obtained by planimetry from 1:50,000 topographical maps, 37 E/6 West and East sheets, Surveys and Mapping Branch, Department of Energy, Mines and Resources). Change in the surface area since 1961, which is of the order of 1 km^2, has been ignored.

The entire glacier surface has approximately the same aspect, and furthermore it is surrounded by ice along most of its perimeter. Local topographical effects are therefore not likely to be of great importance in the general budget pattern. Observations were based on a network of 39 stakes (Figure 4), with a main line of 25 stakes extending straight up the glacier from its snout. A short section of the main line was twinned on the snout (a to a^1), and a second major line was set diagonally across the main area of the glacier. Although

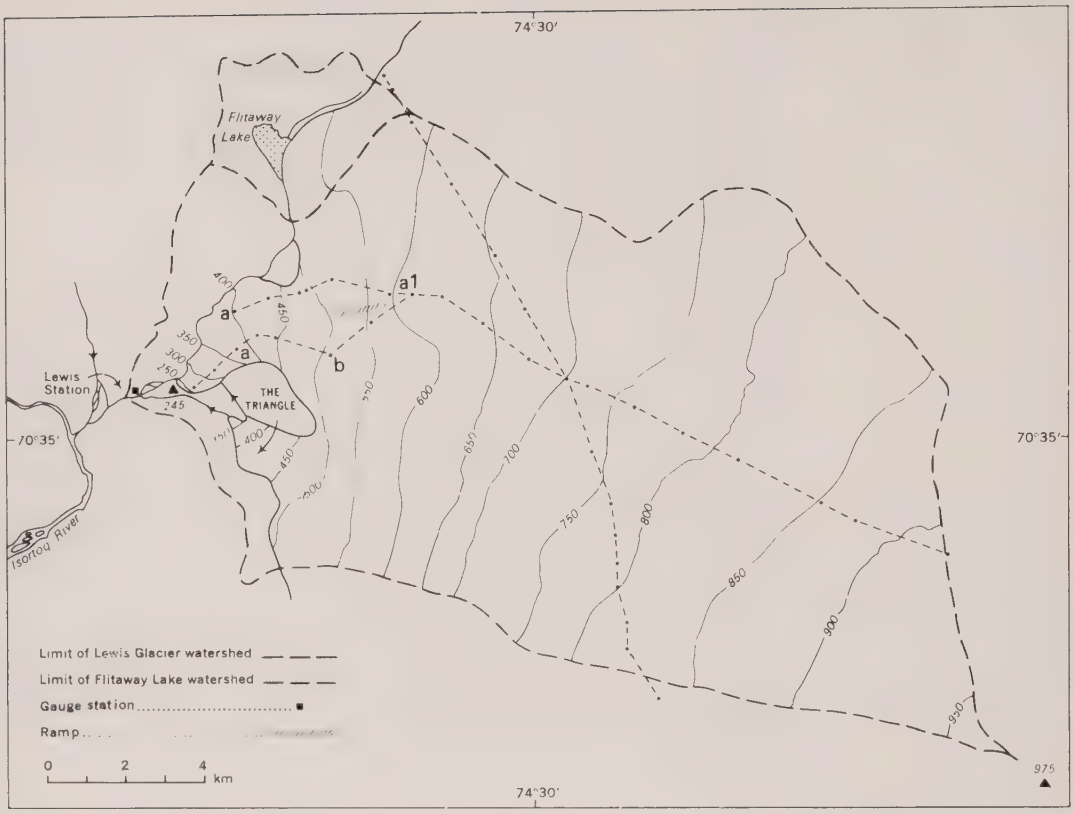


FIGURE 4. Network of ablation stakes on the Lewis Glacier 1964 to 1966. (A temporary stake network was used in 1963).

gaps occur in some places, stakes were established at approximately 30-metre elevation intervals on the lower part of the glacier and about 1 km apart on the upper area. The results of only 38 stakes were used because when runoff began it was discovered that one stake (b) had been placed right at the edge of a meltstream and its observations could not be considered representative.

Snow depth measurements were made along the lines each spring by taking a mean of 10 or 20 measurements in an area of about 500 m^2 around each stake, and by making supplementary soundings along the line between the stakes. Wind-scoured, bare ice zones were specifically noted. Snow cover is always highly variable and therefore, the snow depth measurements should have been extended to many more areas of the glacier. Unfortunately time did not permit this and, as a result, the snow measurements are regarded as the least satisfactory part of this particular glaciological program.

The winter accumulation of snow on arctic glaciers is much less than on glaciers in temperate regions. Furthermore, in all three years of record the Lewis Glacier region lay within that zone of the Barnes Ice Cap where new ice formed directly by the refreezing of percolating meltwater at the base of the snow pack to form superimposed ice (Müller, 1962). Hence no problem of measuring partially metamorphosed firn was encountered. As the entire Lewis Glacier lay within or below this *superimposed ice zone* where all the snow normally disappears during the summer, the new accumulation occurred each winter upon a hard ice surface. Consequently, all snow density measurements were made by using an Adirondack sampler to gain measurements of the mean density of the entire pack.

Snow density measurements made in 1965

at each stake in the network were the mean of 10 measurements, and the results were found to be very consistent along the entire length of the glacier. With the exception of a few sites where fresh snow was measured over previously bare ice, results at individual stations varied from 0.31 to 0.42 gm/cm and the mean for the entire glacier was 0.36 ± 0.03 gm/cc. This result has been taken as representative for the snow pack before the commencement of melt and applied against the 1964 accumulation measurements as well.

The end of the winter accumulation season occurs at different times at different elevations on the glacier, and snow may fall at any time during the summer. During the summer season the field party was stationed off the glacier to make hydrological measurements, and as convenient access on to the snout was made impossible because of the large streams, measurements could not be continued. The accumulation period is arbitrarily regarded therefore as ending when the last spring accumulation measurements have been made, *i.e.,* after the last considerable snowfall. After this date, all summer precipitation was considered as running directly off the glacier, without contributing to its mass change. Although this results in a small underestimate of accumulation and ablation at the upper levels where some of the summer precipitation falls as snow, especially during a cold summer like that of 1964, it will have no effect on the net mass balance accounting.

Ablation data are based on mid-season and end-of-season stake measurements only, and at most stakes, the final ablation measurement was delayed until the following spring when the ice level at the end of the previous season's melt could be ascertained for each pole. The presence of superimposed ice was then identified by an observation of net gain of the ice surface over that of the preceding year. Mass balance data may thus be obtained even though a field party cannot be maintained on the glacier until the very end of the melt season.

THE 1964 MASS BALANCE

Accumulation

The first snow of the 1964 budget year fell on 27 August 1963, and the mid-Baffin Island meteorological records at Dewar Lakes show that the accumulation season began definitively on 1 September 1963, and extended until the end of June 1964. The glacier was first visited between 29 May and 3 June 1964. Some melting began on the lower part of the glacier in early June but as a severe June storm gave about 12 cm of new snow (3.6 cm water equivalent) over the entire glacier, final accumulation measurements were not made until 30 June.

The accumulation map (Figure 5a) shows several characteristic features. The amount of accumulation generally increases up-glacier, partly a result of the greater winter precipitation at higher levels, but it also reflects the influence of the down-glacier winds that blow snow off the marginal slopes of the Ice Cap. This effect is evident on a smaller scale on the Lewis Glacier itself, where the convex slopes are continually swept bare during the winter. Even in spring large areas of bare ice occur on the steep slopes of the snout and on the upper slopes of a "ramp" which lies between 500 metres and 600 metres and marks a prominent break in the surface slope at the head of the glacier. Here, a short, steep rise leads up on to the general Ice Cap surface. Conversely, snow accumulates to greater depths in the hollows of concave slopes. Thus large snowdrifts occur along the margins of the glacier and an area of high accumulation occurs in the hollow below the ramp zone where over 20 cm water equivalent was measured in 1964. Above the ramp accumulation increases very regularly up to a high of 36.5 cm water equivalent measured in 1964 near the last pole at the head of the basin.

Total accumulation on the glacier for 1964, as measured from the accumulation map, was 43.9×10^6 m^3 water equivalent. This represents a mean accumulation over the entire glacier surface of 24.0 cm of water, or about 67 cm of snow, if the average density of the snow pack over the glacier is assumed to be 0.36.

Ablation

Computations for ablation are based on an assumed mean ice density of 0.90. Ablation decreases quite regularly up the glacier (Figure 5a). The high ablation of >200 cm water equivalent, recorded at the snout even in the fairly cool summer of 1964, reflects the extre-

FIGURE 5a
The 1964 mass balance of the Lewis Glacier.

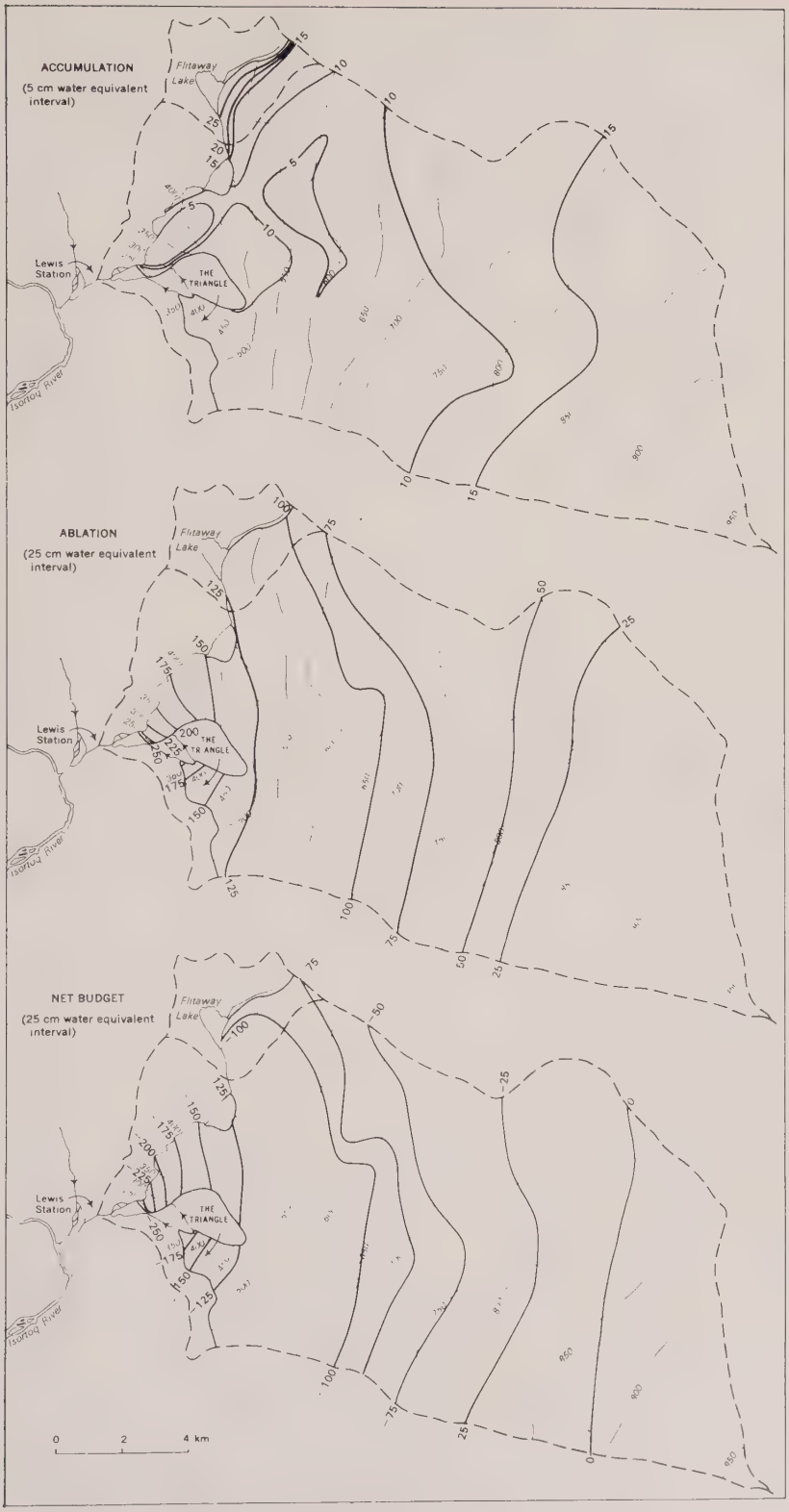


FIGURE 5b
The 1965 mass balance of the Lewis Glacier.

Table 1

Lewis Glacier: Mass budget, 1964
(All budget data are expressed in terms of water equivalent)

Elevation range (metres)	Area (km^2)	Accumulation Specific (cm)	Accumulation Total (10^6 m^3)	Ablation Specific (cm)	Ablation Total (10^6 m^3)	Net budget Specific (cm)	Net budget Total (10^6 m^3)
245–300	0.4	17	0.07	203	0.88	−186	− 0.81
300–350	0.7	8	0.06	163.5	1.18	−155.5	− 1.12
350–400	1.7	8	0.14	147	2.49	−139	− 2.35
400–450	3.3	9.5	0.32	136.5	4.53	−127	− 4.21
450–500	5.2	18.5	0.98	127	6.68	−108.5	− 5.70
500–550	12.9	18.5	2.36	117.5	15.19	− 99	−12.83
550–600	15.6	17	2.61	98.5	15.34	− 81.5	−12.73
600–650	17.1	16.5	2.84	79	13.50	− 62.5	−10.66
650–700	14.0	19.5	2.76	66	9.24	− 46.5	− 6.48
700–750	21.9	23	5.08	59.5	13.02	− 36.5	− 7.94
750–800	23.3	26	6.03	50.5	11.76	− 24.5	− 5.73
800–850	32.4	29.5	9.52	36	11.66	− 6.5	− 2.14
850–900	19.8	31.5	6.26	16	3.16	+ 15.5	+ 3.10
900–950	13.3	34	4.51	4.5	0.60	+ 29.5	+ 3.91
>950	0.8	37	0.30	2	0.02	+ 35	+ 0.28
Totals/Means	182.4	24.0	43.84	59.7	109.25	− 35.7	−65.41

Note: one extra digit is given in these calculations over the results reported in the text.

mely negative regime of the lowest section of the glacier. Because of the regularity of the melt pattern, ablation has been computed from an elevation trend (*see* Figure 6). The total ablation for the summer of 1964 was 109.3 × 10^6 m^3 water equivalent and represents a mean specific ablation of 59.7 cm of water over the glacier as a whole.

One interesting aspect indicated by stake measurements in the spring of 1965 was that the greatest amount of ablation occurred during a single warm period after 14 August 1964. On this date stake measurements showed that total ablation was only 33.0 × 10^6 m^3 water equivalent, and therefore about 70 per cent of the melt occurred between 14 August and the end of the season. In terms of specific ablation, the proportion occurring in this period varied from about 35 per cent on the snout to virtually 100 per cent on the highest areas of the glacier.

Net mass balance

Though the 1964 net mass balance for the Lewis Glacier (Table 1, and Figure 5a) is strongly negative, the equilibrium line nevertheless occurs within the watershed, and for the major portion of the Barnes Ice Cap a positive net budget was indicated for 1964 (Sagar, 1966). On the Lewis Glacier the net budget was −65.4 × 10^6 m^3 water equivalent, giving an average net loss over the whole glacier of 35.7 cm of water. While the transient equilibrium line lay at about 700 metres on 14 August, it had retreated by the end of the ablation season to an elevation of about 825 metres. The altitude distribution of the specific balance components is shown in Figure 6.

THE 1965 MASS BALANCE

Accumulation

The 1965 accumulation season in the Lewis drainage basin apparently did not begin definitively over the entire glacier until 25 September 1964, though most of the precipitation after 7 September was in the form of snow. These dates were determined by inspection of the mid-Baffin Island meteorological record. The accumulation season ended 6 June 1965 with the last significant snowfall. After that a period of fine days marked the transition to the ablation season.

The accumulation (Figure 5b) shows a somewhat similar distribution of snow to that of 1964 but the total fall of 22.2 × 10^6 m^3 water equivalent was only half that recorded in the previous year. Except for an area of deep drifting near the Flitaway Lake edge of the Ice

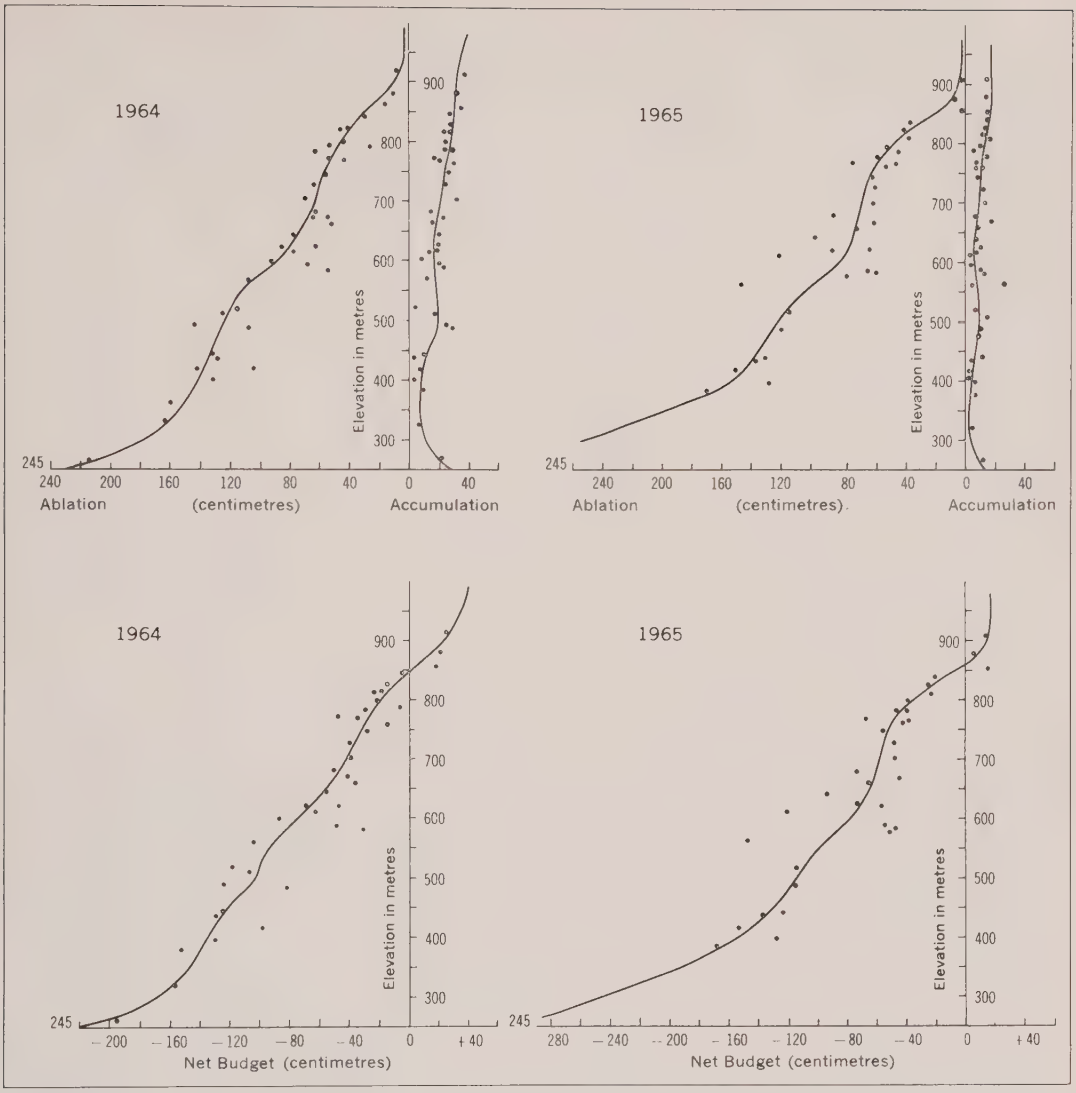


FIGURE 6. Specific accumulation, specific ablation and specific net budget of the Lewis Glacier plotted against elevation for 1964 and 1965.

Cap, the accumulation in 1965 was everywhere less than 20 cm, whereas in 1964 the *mean* value of accumulation was greater than that. In 1965, extensive areas of bare ice occurred on the snout and on the ramp slopes.

The mean accumulation for 1965, averaged over the entire ice surface, was 12.2 cm of water, or about 34 cm of snow at a density of 0.36 gm/cc.

Ablation

Ablation during the 1965 season (Figure 5b) was similar to that of 1964 (Figure 5a) despite the slightly cooler season. However, the critical melt months of July and August were slightly warmer in 1965 and the much lighter snow cover melted relatively soon to expose the glacier ice. Because of its lower albedo and more irregular surface, the ice melts more efficiently than the snow.

The total melt for the 1965 ablation season was 114.7×10^6 m^3 water equivalent, which represents a mean specific ablation of 62.9 cm of water over the entire glacier surface. Once again, a significant proportion of the total melt occurred late in the season. On 13 August,

Table 2

Lewis Glacier: Mass budget, 1965
(All budget data are expressed in terms of water equivalent)

Elevation range (metres)	Area (km^2)	Accumulation Specific (cm)	Accumulation Total (10^6 m^3)	Ablation Specific (cm)	Ablation Total (10^6 m^3)	Net budget Specific (cm)	Net budget Total (10^6 m^3)
245–300	0.4	9	0.04	290	1.26	−281	− 1.22
300–350	0.7	3.5	0.02	223	1.61	−219.5	− 1.59
350–400	1.7	5	0.09	177	3.00	−172	− 2.91
400–450	3.3	7	0.22	148	4.91	−141	− 4.69
450–500	5.2	10.5	0.55	134	7.05	−123.5	− 6.50
500–550	12.9	10.5	1.35	120	15.51	−109.5	−14.16
550–600	15.6	8.5	1.31	96	14.95	− 87.5	−13.64
600–650	17.1	7	1.21	80	13.67	− 73	−12.46
650–700	14.0	9.5	1.33	72	10.18	− 62.5	− 8.75
700–750	21.9	10	2.22	68	14.88	− 58	−12.66
750–800	23.3	12	2.83	58	13.50	− 46	−10.67
800–850	32.4	16	5.13	38	12.31	− 22	− 7.18
850–900	19.8	17.5	3.46	9	1.78	+ 8.5	+ 1.68
900–950	13.3	17.5	2.32	1.5	0.20	+ 16	+ 2.12
>950	0.8	17.5	0.14	1.0	0.01	+ 16.5	+ 0.13
Totals/Means	182.4	12.2	22.22	62.9	114.72	− 50.7	−92.50

Note: one extra digit is given in these calculations over the results reported in the text.

stake measurements indicated a total ablation of 81.1 × 10^6 m^3 water equivalent, so that 29 per cent of the melt occurred after this date. While this is relatively much less than in 1964, the two years' results taken together show that the melt during the later portion of August and early September is extremely important in determining the nature of the budget year. It is during this time when the entire glacier is bare of snow that ice melt proceeds at its fastest rate.

Net mass balance

The net mass balance for 1965 is shown in Table 2 and Figure 5b and the altitude distribution of the budget components is shown in Figure 6. A net mass loss of 92.5 × 10^6 m^3 water equivalent was recorded, giving an average specific loss over the entire glacier of 50.7 cm of water. This is considerably more than the 35.7 cm loss in 1964, and the difference of some 27 million cubic metres of water is made up largely in the accumulation difference between the winters of 1964 and 1965. Nevertheless, as in 1964, the equilibrium line at the end of the ablation season still lay within the watershed (Figure 5b).

Very high ablation was recorded on the glacier snout in both years, specific net loss being well over 200 cm near the margin. Planimetric surveys of the ice margin were carried out at the snout on 13 July 1963, and again on 9 August 1965 (Figure 7). Between the surveys an average retreat of approximately 40 metres occurred with the extreme changes ranging from a small apparent "advance" at a point where the ice was buried in 1963, to a retreat of 60 metres at a point where the ice was being undercut by the north branch of the Lewis River. Along the north margin, the ice cliffs are actively calving as in this area the river undercuts the glacier. Andrews and Webber (1964) have concluded from photographic and botanical evidence that the glacier retreated at an average rate of 43 metres annually between 1938 and 1963. For the generally cool period 1963 to 1965, the rate of retreat was considerably reduced but was nevertheless substantial.

Part II

ACCURACY OF THE MASS BALANCE MEASUREMENTS

Reliability of the Measurements

It would be useful to be able to estimate the precision of mass balance calculations. Several studies have been made of the errors that ap-

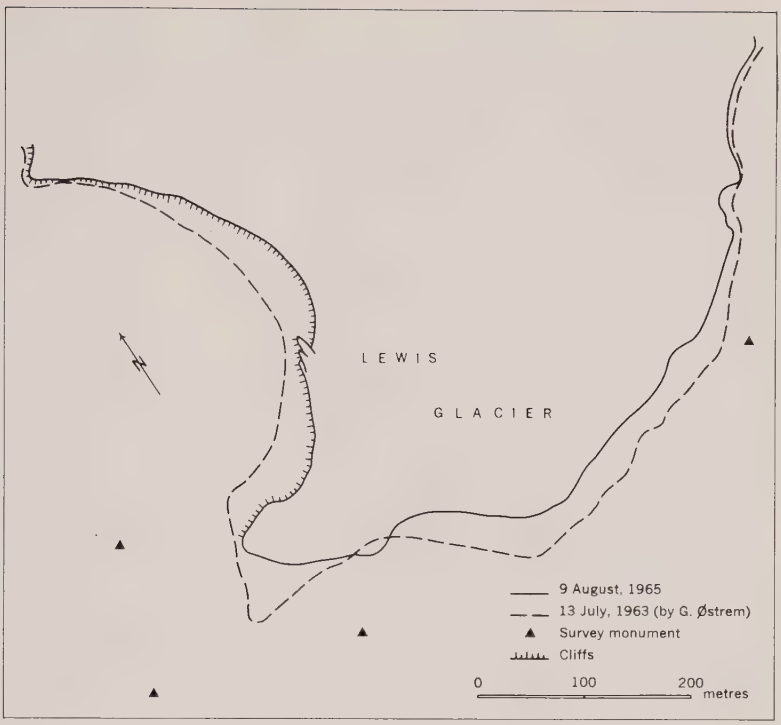


FIGURE 7.
Superposition of planimetric surveys of the Lewis Glacier snout made on 13 July 1963 and 9 August 1965. About 40 metres of retreat up-valley occurred between the two surveys. The entire snout zone of the glacier is presently dead ice.

pear in the measuring of various components, and of the errors of short-term observations. These have been summarized together with the presentation of new data in studies by Adams (1962) and Keeler (1964). The accuracy of stake measurements has been discussed by Bauer (1960) and Untersteiner (1961). Hoinkes and Rudolph (1962) calculated a maximum error of 15 per cent of the average net balance for their measurements over nine years on the Hintereisferner, and Meier and Tangborn (1965) have given standard error estimates with their mass balance calculations for the South Cascade Glacier.

In making measurements on a glacier, two types of error are likely to appear: errors of measurement and errors of sampling.

Errors of measurement are not likely to exceed ± 0.5 cm at a stake at any one time and it appears that in comparison with the error of sampling this factor can be safely ignored in long-term observation.

Errors of sampling – Inasmuch as each stake or snow course is taken to be representative of conditions over a wide area in its elevation zone, the data are subject to sampling error. A series of 15 stakes were established in an area of approximately 1 km^2 at the northern end of the Ice Cap adjacent to the Lewis Glacier region. The stake density in this quadrat corresponds with an optimum value suggested by Schytt (1962). Complete mass balance data for 1963 through 1965 reveal no altitudinal trend within the area. Thus the variation in results obtained in the quadrat arises from local variation in surface exposure, differences of surface albedo, proximity to melt streams, and other local surface features. For snow, the local variation in wind drift is the important factor introducing variation into accumulation measurements. It is the sampling variance arising from all these factors that we wish to assess. Data pertaining to the 15 stakes are summarized in Table 3. In all three seasons all the snow melted away during the summer and there was a net loss of ice in the quadrat.

Not surprisingly, the snow accumulation shows greater relative variation than the ice ablation, though the absolute variance of the ice ablation is greater due to the greater magnitude of the observations involved. The close results for snow and ice in 1965, when their

magnitudes were comparable, is instructive in this regard. The statistics exhibit the usual behaviour of physical data: the absolute deviation becomes larger as the magnitude of the observed data grows, but the relative error becomes less. Furthermore, the magnitude of the sampling error is considerably more stable than the magnitude of the measured variable.

Presumably then, the result from an ablation stake and snow sampling station established in this region to index melt, may be expected to have the computed variance for each season. The standard deviation of this and of similar measurements will be designated in this paper as the *standard error of the measurement*. The standard error of the specific mass balance in areas below the equilibrium line will correspond to that of ice ablation, since this is the total net change – at least in the case of the Lewis Glacier where the pattern of accumulation and ablation is relatively simple and where summer precipitation is considered as transient. However, where the mass balance is positive the situation is different. Here the measurements of snow accumulation become significant, and further, it is likely that the error of superimposed ice measurements will not be the same as that of ice ablation since the pattern of ice formation will, in part at least, depend on the snow cover. There being no quadrat measurements from an area of accumulation on the Barnes Ice Cap, the best approximation to sampling error that can presently be made for such areas is to pool the error of snow sampling twice over – once for accumulation and once for ablation – and so establish figures of merit of ± 7.2 cm or 39 per cent for 1964, and ± 11.8 cm or 33 per cent for 1965. The relative errors are referred to mean snow depth data from the quadrat.

How these errors apply over the entire surface of the glacier is not clear. As extreme cases it may be assumed either that the sampling error is stable and applied equally to any stake measurement, or that the sampling error is simply proportional to the magnitude of the observed datum and that, as the magnitude of the observation becomes smaller, so does the probable error. In the latter case it can be seen that, in the limit of there having been no ablation or accumulation during some period after a measurement, a new measurement made at the end of that period will have no sampling error. The first case corresponds to a constant absolute standard error over the entire glacier – here for example, equal to ±8.4 cm for snow, and ±8.0 cm for ice ablation in 1965 (Table 3), while the second case corresponds to constant relative error – here equal to ±23.9 per cent of the observation for snow accumulation and ±22.9 per cent of the observation for ice ablation in 1965. Though the true situation appears to lie between these two cases, it will be assumed in the present absence of further information, that the absolute error is the same over all areas of the glacier. It appears to be the more stable of two statistics because it does not depend directly on the size of the measurement, but only on the dispersion of sample values about it. To come to any valid conclusions in this matter would require an exhaustive study which has not been possible in the present investigations (*see* however, Adams 1962, pp. 12-19).

Errors due to arithmetical simplifications

In addition to measurement and sampling errors, further error may enter into the calculation of the mass budget due to the arithmetical simplifications that may be made. Interpolation of the budget may be either from a map or from an altitude trend. Each method has its advantages. A map is most advantageously used for a set of observations that show no clear spatial trend, or that have great variability. This commonly applies to snow accumulation observations. Use of a map avoids having to make the assumption that a trend line is representative over the whole glacier. On the other hand, data that show a clear altitude trend can be conveniently cumulated from such a trend line and the error of the trend is far easier to assess than are map errors. On the Lewis Glacier the ablation and net mass balance show clear trends and can be treated in this way. The fact that the data were collected from a basically linear stake-network that runs up-glacier probably accentuates this fact, however, and this could easily lead to biased results if the data are not carefully evaluated in this matter beforehand.

Subjective errors

Total accumulation on the glacier has been measured from an accumulation map con-

Table 3

Variance computations for the sample quadrat: Barnes Ice Cap, north end (15 stakes) (All data are expressed in terms of water equivalent)

Datum	Snow accumulation			Ice ablation		
	1963	1964	1965	1963	1964	1965
Mean depth in cm	19.8	18.6	35.2	49.4	46.1	34.9
Variance	36.8	25.9	70.2	59.4	50.0	63.9
Standard deviation	±6.1	±5.1	±8.4	±7.7	±7.1	±8.0
Standard deviation expressed as a percentage of the mean	±30.8	±27.4	±23.9	±15.6	±15.4	±22.9

structed from the snow depth measurements along the line of stakes (Figure 4), and in the production of this map new, intangible sources of variation emerge. Inevitably the interpolation of isopleths depends in some degree on the surveyor's own experience of the particular glacier, on a knowledge of past conditions and the topographic relations of drifting. Here is a subjective element that it is not possible to measure with the data in hand (*see* Meier and Tangborn, 1965, where the same problem is briefly discussed). The estimates of sampling error can stand, then, only as minimum values.

In computing the total net mass balance, the trend of specific net balance versus elevation was first established by interpolation among the observed datum points. While no least squares criterion was used, the trend was adjusted so that the sum of the deviations of the observed datum points was zero. Variance of the individual stake data about the trend was computed and the results are given in Table 4. To obtain a standard error for the net mass balance both the measurement error and the computational error must be considered. The measurement error has thus been pooled with the trend error as

$$E_T = \sqrt{(\text{sampling error})^2 + (\text{trend error})^2}$$

where the sampling error has been adjusted* so that the separate errors applicable to the areas of the glacier above and below the equilibrium line have both been considered. The results give a total error for a net mass balance estimate of

$$E_{T.\,1964} = \pm 16.60 \text{ cm}$$
$$E_{T.\,1965} = \pm 20.94 \text{ cm}$$

The mean net mass balance is based on 15 altitude range zones. Hence the standard errors of the mean values for the entire glacier are as follows:

$$E_{T.\,1964} = \frac{\pm 16.60}{\sqrt{15}} = \pm 4.29 \text{ cm};$$

$$E_{T.\,1965} = \frac{\pm 20.94}{\sqrt{15}} = \pm 5.41 \text{ cm}^{**}$$

Table 4

Variance about the net budget trend: (All data are expressed in terms of water equivalent)

Datum	1964	1965
Weighted mean specific net budget in cm (weighted by area-altitude distribution)	−35.7	−50.7
Variance of individual measurements about the trend	223.8	359.0
Standard error of individual measurements	±15.0	±19.0

*The weighted sampling error for 1964 is $\frac{7.1 \times 126.7 + 7.2 \times 55.7}{182.4} = 7.13$ cm, and for 1965 is $\frac{8.0 \times 142.9 + 11.8 \times 39.5}{182.4} = 8.82$ cm. The multipliers are the areas of the glacier above and below the equilibrium line.

**The standard error of the mean is normally given by the number of measurements represented in the mean. This would give an error of the mean net mass balance of $\frac{\pm 16.60}{\sqrt{38}}$ for 1964, for example, since 38 datum point were used to establish the mass balance trend. However, the fitted trend is not a least squares fit and one cannot be sure that the trend mean is the true one. Hence, the mass balance was aggregated by reading 15 new values off the trend and using these to compute the total mass balance by elevation zones. This is clearly a less efficient procedure, and is paid for with a higher error margin; but it is in less danger of bias. In fact, as many as 38 new "zone estimates" of net mass balance could be read from the trend (equal to the number of observations used to establish the trend), but in general, probably not more than n/2 (here, 19) estimates should be read back from a trend constructed in this way. The rule is purely heuristic

These data represent relative errors of ±12.4 per cent (1964) and ±10.7 per cent (1965) of their respective net balance. These must still be regarded as minimum estimates. These errors give a total net mass balance for the Lewis Glacier, based on a two standard error range of

-65.4×10^5 m³ water equivalent $\pm 7.8 \times 10^5$ m³; for 1964;

-92.5×10^5 m³ water equivalent $\pm 9.9 \times 10^5$ m³; for 1965.

It may seem odd that the glacier area has not been directly considered in assessing the error of the budget. It is reasonable to suppose that had there been a higher stake density, *i.e.*, many more stakes, the results should have exhibited less variance or, what amounts to the same thing, if the glacier area had been much smaller for the same number of stakes, the results should have been more reliable. In fact, making spot samples on the surface of the glacier – where there are any number of sampling points – is an example of the problem which arises when a sample of observations is made from an infinite population. The population of possible sampling points cannot therefore, be conveniently related to the area of the glacier and thus, no explicit relationship between the sample and the size of the glacier can be stated.

The size of the glacier does however, enter the analysis implicitly in several ways. In the matter of sampling it has been assumed that the stake network has given a representative picture of the glacier mass balance; if it has not, an undetected bias will exist in the data. This assumption becomes more reasonable as the density of stakes becomes greater, for then there is a more complete sampling of the glacier surface. Again, in computing the net mass balance, the variance of the data was seen to depend on two factors:

– variability of local conditions on the surface, assessed as sampling error;

– departures from the specific net balance trend.

It is reasonable to suppose that the more dense the network of stakes, the more precise may be the trend interpolation. With a greater stake density more information on the true nature of the trend is obtained and so the error of assumption as to its form involved in drawing the trend line, is correspondingly reduced. The trend error, then, contains an element which depends on the intensity of observations (*see* Schytt, 1962). The same consideration applies to map interpretation when mass balance assessments are made in that manner.

As a check on the net balance calculations, the mass balance was also measured by planimetry from the maps shown in Figures 5a and 5b. The result for 1964 gave -71.6×10^6 m³ water equivalent. Though somewhat higher than the result given in Table 1, it falls within the indicated upper error margin of -73.2×10^6 m³. For 1965, the map computation gave -92.5×10^6 m³ water equivalent, in precise agreement with the result from Table 2. Because of the uncertainties of map interpretation, and because of the finer division of the glacier surface achieved by the trend computations, the latter are here regarded as the more reliable results.

Part III

THE WATER BUDGET OF THE LEWIS RIVER, AND EVALUATION OF ITS RELIABILITY

During the ablation seasons of 1963, 1964 and 1965 a water budget was kept for the Lewis River drainage basin. The river drains the entire watershed area through one channel that flows through a 65-year old moraine of the Lewis Glacier (Andrews and Webber, 1964) about 1¼ km from the present snout. Here it was possible to establish a gauging station to measure stream flow. One complication in the measurement of runoff from the basin is the presence of Flitaway Lake, an ice-marginal lake that is the source of the Lewis River proper. Each spring the lake is dammed behind a snow and ice barrier that persists until the latter part of the summer. After the dam is first breached the remnants of the ice plug are rapidly washed out. Thus the lake contributes the major portion of its discharge to the river within a relatively short period near the end of the season. The contribution of Flitaway Lake has, therefore, been separately treated in the water budget.

The characteristics of the river basin are as follows:

	Ice (km^2)	Land (km^2)	Total (km^2)
Flitaway Lake drainage area	4.3	7.2	11.5
Direct Lewis River drainage area	178.1	15.8	193.9
Total area	182.4	23.0	205.4

Area of Flitaway Lake	0.63 km^2 (1963)
Highest elevation in the watershed	965 metres (on ice)
Gauge elevation	230 metres
Total relief in the gauged basin	735 metres
Maximum runoff length (along the channel)	25 km

Note that 88.8 per cent of the watershed area is on ice.

COMPOSITION OF THE WATER BUDGET

The water budget was compiled from runoff records obtained at the gauge, precipitation records kept at the river station, observations of Flitaway Lake levels, snow accumulation records for the basin, and ice ablation observed on the glacier. Error analysis was attempted for the 1964 and 1965 records.

Runoff

Runoff was measured at the stream gauge of the Lewis River. Both staff and automatic gauge records were kept but, as it proved difficult to keep the automatic gauge reliably operational, the record has been mainly synthesized from the staff measurements, using the automatic gauge trace to fill in the record where gaps appear. At least twelve staff measurements were taken during a normal day, and often many more. In 1963 the total measured discharge was 168.0×10^6 m^3 of water. This was much more than in 1964, when only 60.5×10^6 m^3 were measured. The periods of record are not strictly comparable, however, as the 1963 record covered virtually the entire runoff season (June 25 to August 23) while the 1964 record (May 31 to August 14) was ended early. In a comparable period in 1963, 134.1×10^6 m^3 water passed by the gauge while in 1965 only 99.6×10^6 m^3 water passed by the the gauge in a similar period of record.

The rating curve of the Lewis River station was established by a combination of current metre and relative salt dilution measurements of discharge. The rating curve standard error is large: +17.2 per cent or −14.7 per cent for an individual flow estimate.*

*The error is asymmetric because the rating curve is a power relationship. Computations were carried out in $\log_{10}$ units, and the error was ±0.069. Some error undoubtedly occurred as errors of the discharge measurements, but the factor cannot be isolated and so must be ignored.

For longer term compilations of runoff, however, the error should be compensating. Individual discharge measurements were submitted to autocorrelation analysis for selected 24-hour periods, and the 24-hour compilation of flow was analyzed over the full season. After removal of the diurnal trend there was no significant autocorrelation in the daily runoff pattern at the 90 per cent confidence level. Inasmuch as observations were spaced at approximately hourly intervals, this indicates that there is no major flow cycle present whose period falls between about 2 and 24 hours. This conclusion is confirmed upon examination of the flow hydrograph from the automatic gauge. On the other hand, the daily runoff over the season gave highly significant results, as seen in Table 5. The value of r_1 (u) is significantly lower in 1963 than in the other two years. The hydrographs of flow (Figures 8, 9 and 10), show that runoff was much more regular during 1963 than during 1964 and 1965, being dominated in 1963 by normal ice ablation. Fluctuations about the runoff trend for 1963 are fairly regularly distributed. By contrast, the 1964 and 1965 summers were both cool with little melt, and runoff patterns were dominated by periods of rainfall and cold temperatures. Consequently departures from the seasonal trend of runoff persist in the record for periods of several days and the data show a high degree of autocorrelation.

Table 5

Autocorrelation of daily runoff totals: Lewis River

Season	$r_1(u)$	N	Significance (per cent)	N'
1963	0.296	70	>95	35
1964	0.561	64	>99	19
1965	0.571	72	>99	21

where

$r_1(u)$ indicates autocorrelation with one lag, and u represents runoff residuals after removal of the seasonal trend;

N is the number of observations (number of days of record);

N' is the equivalent number of independent observations.

Computations are based on the methods of Matalas (1963).

Allowing 12 observations for the daily record of runoff, the $\log_{10}$ standard error of the 24-hour mean flow is

$$E_{24} = \frac{\pm 0.069}{\sqrt{12}} = \pm 0.020.$$

This is the same as +4.7 per cent or −4.3 per

cent, and applies also to the compilation of flow. For the season we have $\frac{\pm 0.020}{\sqrt{N'}}$ as follows:

1963	±0.8 per cent
1964	±1.0 per cent
1965	±1.0 per cent

A two standard error limit of ±2.0 per cent is used for the 1964 and 1965 runoff totals.

The *Flitaway Lake* contribution to runoff has been separately established by a survey of lake levels, and the amount is fairly constant for 1963 and 1964; about 2×10^6 m^3 water. In 1965, only 0.8×10^6 m^3 drained away. Inasmuch as the snowdrift barrier in the ice-marginal channel draining the lake was not breached in any year until the final week of record, the total runoff contribution of the lake and its drainage area has been taken to be essentially this single contribution. Any additional precipitation and melt occurring through the lake basin after it became an active part of the drainage system have thus been ignored.

The survey error for the lake levels is assessed as ±10 cm, due mainly to the problem of determining exactly the high water line. This gives an error estimate for the Flitaway Lake drainage of ±3 per cent in 1964 and ±8 per cent in 1965.

Precipitation

Precipitation was measured by a gauge at the Lewis station located at an elevation of 233 metres. The observations are summarized in Table 6. The 1965 precipitation is virtually twice as great as the total for 1963. This is not due to the difference in the periods of record, for in 1965 the season's total precipitation was increased by two exceptional storms that occurred in the latter part of July, giving 9.7 cm of rain. This represents about 70 per cent of that season's total precipitation.

The most common pattern of summer precipitation in the area is for clouds moving in from the west or southwest along the Isortoq valley, to rise over the edge of the Ice Cap giving local showers. Precipitation along the ice margin is thus in part orographic. On many days rain fell on the glacier while no rain fell at the station. On the other hand, the major regional storms that account for a large amount of the total precipitation probably deliver precipitation fairly evenly over the entire watershed. During the 1964 season a meteorological station at an elevation of 580 metres was in operation at the margin of the Ice Cap north of Flitaway Lake, just at the edge of the Lewis drainage area. Measured precipitation here was 10.6 cm for the period June 23 to August 18, while at the Lewis River station it was only 6.8 cm for the same period. Thus about 1.5 times as much precipitation fell at the ice margin station as at the Lewis River station and the Lewis River gauge appears then to underestimate the precipitation in the watershed.

Table 6

*Summary of precipitation at Lewis station, 1963-1965**

	1963	1964	1965
Period of record	25 June–23 August	8 June–18 August	25 May–13 August
Measured precipitation in cm	7.4	9.1	13.6
Indicated total precipitation for the watershed	14.3×10^6 m^3	17.6×10^6 m^3	26.4×10^6 m^3

*In order to avoid double counting, the area draining to Flitaway Lake was not included in these computations.

Further, rain gauge catch usually underestimates the actual precipitation. Error estimates for the catch of the gauge have been made from a graph of rain gauge deficiency with wind speed given by Linsley, Kohler and Paulhus (1958) and attributed by them to W. T. Wilson. Underestimates vary from 2 per cent (rain) or 20 per cent (snow) at winds of 5 km hr.$^{-1}$ to 43 per cent (rain) or 63 per cent (snow) at winds of 30 km hr^{-1}. Results totalled over a whole season on the basis of precipitation and accompanying wind measurements made at Lewis station for each recorded storm were as follows:

Year	Indicated deficiency of rain gauge catch*
1963	5.5
1964	13.6
1965	22.3

*As per cent of total recorded precipitation.

The 1963 Lewis record is undoubtedly low, as the only available wind estimates were for "present wind" at standard observation hours. The 1964 and 1965 data utilize run-of-wind data for the periods during which rainfall was

observed. The deficiency calculated for the Lewis station in 1965 was inflated by the large deficiency sustained for the first major storm in late July. Winds averaged more than 30 km hr^{-1} through a major part of this storm.

As both the gauge catch error and the possible bias due to non-representative sampling at the Lewis station are negative, it is very likely that the recorded results are too low. For 1964 a figure of merit of –20 per cent was arbitrarily chosen to represent the outside error limit of the precipitation measurement, while for 1965, a value of –25 per cent was adopted, in keeping with the larger indicated gauge catch deficiency.

Snow storage

Snow storage represents the amount of snow present in the watershed at the beginning and end of each season. Though all the measured snow courses were on the glacier, the land area is such a small proportion of the watershed that an adjustment of the result from observations on the glacier is not thought to have introduced any appreciable error. Accordingly, spring snow storage data adopted for the water budget calculations were arrived at by multiplying the glacier snow storage on the date at which the water budget accounting was begun by the ratio of total watershed area/area on the glacier.

The party arrived in the field in 1963 too late to carry out detailed snow surveys. Reconnaissance carried out then and compared with later seasons' results suggests that snow conditions in 1963 were quite similar to those of 1965, when 22.8 $\times$ 10^6 m^3 water equivalent was measured in the watershed on 28 May. On this basis an estimate of 25 $\times$ 10^6 m^3 water equivalent was allowed for 1963 snow accumulation. In 1964 much heavier snowfall occurred and observations indicate that on 30 May 1964, there was 39.9 $\times$ 10^6 m^3 water equivalent in the watershed. Once again, the Flitaway drainage area was excluded from the computations. The following data give specific depth estimates for the snow cover in the area at the beginning of the period of record:

Season	Water equivalent (cm)	Snow (density = 0.36) (cm)
1963	13.0	36.0 (estimated)
1964	20.6	57.2
1965	11.8	32.6

There was no significant snow storage in the watershed at the end of the period of record in August in any of the three years.

The snow cover data were computed from map interpretation. The error analysis of mass budget data (*see* p. 242) indicated that individual snow courses are subject to a standard error of about 28 per cent. Superficially, the errors should compensate on the map; however, new errors of map interpolation and measurement have entered as well. Thus, though the standard error of the mean value for the 38 snow courses in the watershed would be indicated as $\pm$5 per cent, a more reasonable estimate is probably of the order of $\pm$10 per cent – about twice the indicated amount – with a maximum error estimate of $\pm$20 per cent.

Ice ablation

Ice ablation represents the total ablation of ice from the glacier, and for purposes of compiling the water budget has been computed from stake ablation. Inasmuch as net addition to the amount of ice on the glacier may occur through the formation of superimposed ice from snow meltwater, this term may be negative over part or all of the glacier. It represents the net change in the ice mass of the glacier. In 1963, 112.8 $\times$ 10^6 m^3 water equivalent of ice melt was recorded for the period of record from stake observations made on 24 August. This is in strong contrast to 1964, when there was a net addition of new ice *i.e.*, "negative ice ablation", of 6.3 $\times$ 10^6 m^3 water equivalent during the period of observation ending on 14 August. The equilibrium line at the end of the 1964 period of water budget observations lay at an elevation of about 700 metres, indicating that a net addition of ice was recorded over about 60 per cent of the glacier surface. In 1965 the net ablation at the end of the period of record on 13 August was 55.3 $\times$ 10^6 m^3 water equivalent.

The error analysis of the mass balance data indicated that the standard error of individual ice melt measurements was $\pm$7.1 cm in 1964 and $\pm$8.0 cm in 1965, while for areas where net addition of superimposed ice gave net ice accumulation, figures of merit of $\pm$7.2 cm (1964) and $\pm$11.8 cm (1965) were adopted. For the trend error in computing total ablation during the water budget period the data shown

in Table 7 were computed. An analysis similar to that presented for net mass balance shows the absolute specific error of the mean to be ±4.42 cm for 1964, or ±126 per cent of the mean. This high relative error stems from the near-equilibrium condition of the glacier and illustrates how difficult it is to diagnose an actual equilibrium state. The maximum error was taken to be ±252 per cent of the mean as the maximum error, indicating that there might even have been a net ice loss during the period. For 1965, the absolute error appears to be ±4.30 cm, or ±13.9 per cent of the mean. The maximum error was taken to be ±28 per cent of the mean.

Table 7

Variants about the ice ablation trend: Lewis Glacier (All data are expressed in terms of water equivalent.)

Datum	1964	1965
Weighted mean specific ice ablation in cm (weighted by area-altitude distribution)	−3.5	31.0
Variance of individual measurements about the trend	241.5	190.8
Standard error of individual measurements	±15.5	±13.8

COMPUTATION OF THE WATER BUDGET: 1963 TO 1965

The total and specific water budget based on all the above factors is shown in Table 8. The large difference in the total budget between 1963 and 1964 is due to the colder summer of 1964 which resulted in a drastic change in the contribution from ice ablation. Clearly, the contribution of ablation dominates the hydrology of the basin.

Accuracy of the budget: 1964 and 1965

The budget has been recomputed for 1964 and 1965 in terms of the errors of measurement already discussed, and the results are presented in Tables 9a and 9b. As the error ranges of discharge and runoff composition overlap, the discrepancy in the water budgets can be assigned to errors of measurement. The analysis suggests that an outside discrepancy of as much as +67 per cent or −17 per cent of runoff composition might have occurred in 1964 without particular significance, while in 1965 errors as great as +13 per cent or −11 per cent might have occurred. In light of this the budgets attained appear to be in good balance.

Table 8

The water budget of the Lewis River watershed: 1963-1965 (All data are expressed in terms of water equivalent)

Period	1963 25 June–23 August		1964 31 May–14 August		1965 29 May–13 August	
Budget component	Specific* (cm)	Total (10^6 m^3)	Specific* (cm)	Total (10^6 m^3)	Specific* (cm)	Total (10^6 m^3)
Runoff (Q)	81.8	168.0	29.4	60.5	48.5	99.6
Precipitation	7.4	14.3	9.1	17.6	13.6	26.4
Snow storage: May	13 (est.)	25 (est.)	21.1	40.9	11.8	22.8
August	—	—	—	—	—	—
Flitaway net outflow	20.0	2.3	17.8	2.1	7.8	0.9
Ice ablation	63.3	112.8	−3.5	−6.3	31.0	55.3
Sum of the elements of runoff composition (C)	75.2	154.4	26.4	54.3	51.3	105.3
Discrepancy (Q-C)		13.6		6.2		−5.7
Runoff as a percentage of runoff composition		109.0		109.4		97.5

*Note: that the specific budget values will not add up, as they are computed for the area to which they apply, which is not the same in all cases:
—runoff is computed over the entire watershed;
—precipitation is computed over the direct Lewis watershed: that is, the total watershed less the Flitaway drainage zone;
—snow storage is computed over the direct Lewis watershed;
—Flitaway net outflow is computed over the Flitaway drainage zone;
—ice ablation is computed over that portion of the glacier which falls in the direct Lewis watershed;
—total runoff composition is computed over the entire watershed.

Table 9a

Error analysis of the 1964 water budget
(All data are expressed in terms of water equivalent)

Budget component	Observed value (10^6 m^3)	Specific error (per cent)	Absolute error (10^6 m^3)	Upper estimate (10^6 m^3)	Lower estimate (10^6 m^3)
Runoff (Q)	60.5	±2	±1.2	61.7	59.3
Precipitation	17.6	−20	−3.5	21.1	17.6
Snow storage: May	40.9	±20	±8.2	49.1	32.7
Flitaway net outflow	2.1	±3	±0.1	2.2	2.0
Ice ablation	−6.3	±252	±15.9	9.6	−22.2
Total (C) and pooled error of the elements of runoff composition*	54.2	+31.0 −31.3	+16.8 −17.2	71.0	37.0
Discrepancy (Q-C)	6.2			−11.7**	+24.7**
Runoff as a percentage of runoff composition	109.4			83.5	166.8

Table 9b

Error analysis of the 1965 water budget
(All data are expressed in terms of water equivalent)

Budget component	Observed value (10^6 m^3)	Specific error (per cent)	Absolute error (10^6 m^3)	Upper estimate (10^6 m^3)	Lower estimate (10^6 m^3)
Runoff (Q)	99.6	±2	±2.0	101.6	97.6
Precipitation	26.4	−25	−6.6	33.0	26.4
Snow storage: May	22.8	±20	±4.6	27.4	18.2
Flitaway net outflow	0.9	±7	±0.1	1.0	0.8
Ice ablation	55.3	±28	±15.5	70.8	39.8
Total (C) and pooled error of the elements of runoff composition*	105.3	+14.3 −15.6	+15.1 −16.4	120.4	89.7
Discrepancy (Q-C)	−5.7			−22.8**	+11.9**
Runoff as a percentage of runoff composition	97.5			78.8	113.4

*Values on this line are error sums, and not direct sums of the components listed above. The specific error was computed as an area weighted error sum:

$$\sqrt{\frac{\Sigma(\text{absolute error of the component})^2 \times (\text{area to which the component pertains})}{(\text{total area of the watershed})}}$$

**Gained by matching the upper estimate of runoff with the lower estimate of runoff composition, and vice versa. These give outside error limits.

Several residual factors of the water budget have not been taken into consideration, but their total effect must be minor. They include:

– *Unmeasured stream discharge travelling under the channel bed.* As the channel is in unconsolidated deposits there will be some flow under the bed. The amount of such flow has been measured only once in a proglacial situation and was found to be negligible (Hjulström, 1955).

– *Calving of ice cliffs at the glacier snout.* The north side of the snout has high cliffs and is retreating about 20 metres annually along a front some 1,500 metres in length. The ice blocks fall into the Lewis River, whose undercutting activity along the ice margin maintains the cliffs. The cliffs are about 20 metres high on average, so this undercutting activity contributes about 0.6 × 10^6 m^3 water equivalent to the river each season.

– *Evaporation and condensation on the glacier.* Calculations using a modified "Lake Hefner" formula for estimating evaporation and condensation suggested that, over the summer season, these two factors would approximately balance out, and that in any case, their total magnitude on this arctic glacier is relatively minor.

– *Change of storage in the basin.* Water may be stored under the snout of the glacier, which has several known subglacial passages and caves. In addition several ephemeral ponds occur along the south side of the snout. No estimate of their capacity or activity has been possible.

Estimate of glacier net budget from runoff records

One major purpose of the investigations was to determine whether stream discharge can reliably indicate periodic and seasonal melt from the glacier. By subtracting all other factors from stream discharge an estimate of net budget can be made for the season. Where all the snow has melted or has been converted to new ice, the net budget estimate is the same as the "ice ablation" term in the water budget. The budget at the end of the period of record in each of the three seasons is shown in Table 10.

Table 10

Glacier net budget estimated from the runoff records

Season	Ice melt by direct measurement (10^6 m^3)	Ice melt computed from water budget (10^6 m^3)	Discrepancy (10^6 m^3)
1963	112.8	126.4	13.6
1964	−6.3	−0.1	6.2
1965	55.3	49.6	−5.7

Note that in the 1963 budget, the snow storage term was only estimated and might itself introduce a considerable discrepancy into the calculations.

The relative error of the water budget estimate – expressed as a percentage of the direct measurement – was 12.3 per cent in 1963 and 10.3 per cent in 1965, but in 1964 it was 98.3 per cent. The discrepancies of the estimates are the same as the total discrepancies of the water budgets, and inasmuch as the error analysis showed that considerably greater discrepancies than those actually observed were possible, the accuracy of the estimates might easily have been much less again. The significant proportions of relative error in 1964 illustrate the general problem of measuring phenomena whose value may be near zero and thus well within almost any error margin that can be established for the data. It is seen that in 1964 the mass balance equilibrium lies within the maximum error margin.

However, in this same year (1964) the ice ablation estimated from runoff, -0.1×10^6 m^3 water equivalent, falls well within the upper standard error margin (+126 per cent of the observed value of 1.6×10^6 m^3). It may be concluded that the estimate of melt from runoff appears to be as reliable as direct measurement. The consistency of the result computed by two independent methods lends confidence to the belief that the net mass balance data are correct and unbiased, within the error margin.

In light of this the 1963 water budget may be examined to gain an estimate of the 1963 glacier net mass balance. The 1963 runoff record covers all but about two days of significant streamflow, a severe storm commencing on 27 August having abruptly ended the budget year. The 1963 net mass balance may then be established as -126.4×10^6 m^3 water equivalent. Specific net mass balance was −70.9 cm.

Comparison with the 1964 and 1965 final net mass balance shows the 1963 and 1965 net balance to be considerably more negative than that for 1964. This is due in large part to the heavy accumulation of 1964.

Part IV

EFFECTS OF SEASONAL WEATHER ON THE GLACIER

The differences among the water budgets reflect a fairly sensitive reaction to the different weather patterns of the three summers, summarized in Table 11 and together with runoff data, shown graphically in Figures 8, 9 and 10.

The 1963 season shows a very regular hydrograph. The first small discharge peak in early July was provided by the season's heaviest rain, but after that rising discharge followed increasing temperature until 1 August. The highest daily runoff – nearly 9 million cubic metres on 2 August – followed the highest daily mean temperature on 1 August though some rain fell during this period also. Through early August, when the bulk of the seasonal runoff occurred, the high daily discharges were not so much a result of extraordinary peak flows as of high water stage throughout the 24-hour period. Frequently clouds held overnight temperatures at a very high level.

Table 11

Summary of summer climate at Lewis station: 1963, 1964, 1965

Period	Mean temperatures (°C) Maximum	Minimum	Mean	Precipitation (in mm)	Cloud (in tenths)
1963					
June (last 17 days)	7.9	−0.4	4.1	4	6.5
July	9.7	2.6	6.6	57	6.5
August (first 24 days)	10.2	3.5	7.0	13	8.0
Season	9.4	2.2	6.1	74	7.0
1964					
June (last 23 days)	4.0	−0.9	1.7	22	9.3
July	9.3	3.0	5.9	56	7.7
August (first 14 days)	7.6	2.0	4.9	13	6.4
Season	7.1	1.5	4.3	91	8.0
1965					
June	4.8	−1.8	1.4	8	7.1
July	8.4	3.9	6.2	110	7.2
August (first 12 days)	7.6	2.8	5.4	18	9.2
Season	6.8	1.3	4.1	136	7.4

The 1964 pattern of runoff is in sharp contrast to this. A cooler season, particularly in August, produced virtually no ablation, and the runoff was dominated by several peaks determined by precipitation. Consequently, the seasonal runoff trend was virtually non-existent and alternate periods of "above average" and "below average" discharge persisted for several days. This resulted in the high autocorrelation of 1964 flow discussed on p. 247. It is interesting to note that when the station was closed down in mid-August 1964, a warm period was just beginning which, as indicated in the glacier mass budget discussion, apparently produced the bulk of the 1964 melt.

The 1965 runoff was again dominated by storm peaks. There was, however, a consistently higher contribution from glacier melt than in 1964, particularly during the last days of July and early August. The season's most active melt occurred between 23 July and 29 July and, combined with the recession flow from the storm of 20-22 July, produced the highest daily runoffs of the summer.

In a watershed where runoff is dominated by the pattern of glacier melt, a fairly clear correlation is to be expected between available heat supply and runoff – due allowance being made, of course, for precipitation. The most commonly used index of heat supply near the ground surface is air temperature, and to investigate this relationship, cumulated runoff has been plotted against cumulated positive Centigrade degree-hours (*see* Keeler, 1964) for the duration of the records (Figures 11, 12, 13). The cumulated degree-hours provide an easily measured index of the amount of heating that has occurred over the glacier and of the duration of heating. The contrast in the graphs provides a clear indication of the individual character of each season. On the graphs, a steep slope indicates a great *sensitivity* of runoff to increasing heat supply; where the slope of the graph is steeper, a greater increment of discharge occurred for the same increment of heat than occurred where the graph is less steep. The glacier can be said to be "more sensitive" in its response to a given heat increment when a greater amount of water flows off it. However, rainfall, which runs off immediately, will provide an upward shift in the graph: total runoff may increase without there being any coordinate increase of heating.

The 1963 season produced a smooth graph dominated by glacier melt during a relatively warm season, while the irregular graphs of 1964 and 1965 reflect rather the haphazard dominance of storm runoff during seasons of lesser melt.

The graphs have been divided into several periods for further study. All three seasons began with a period of low runoff and a very insensitive response to heating indicated by the initial low slope of each graph (period 1) which extended into early July. Runoff at this time was from snow melt, mainly off the land.

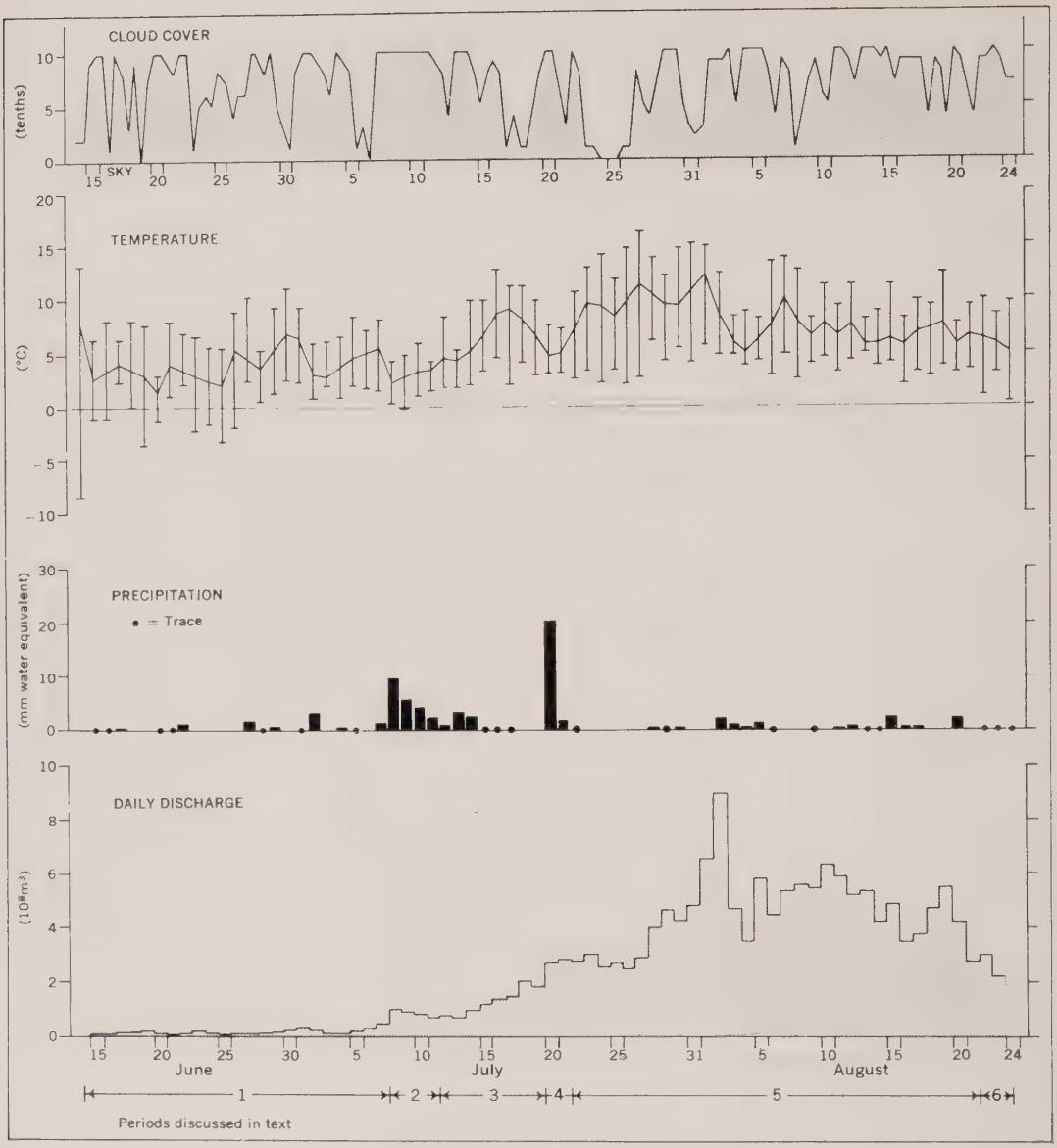


FIGURE 8. Weather elements and stream flow at Lewis station, during the field season of 1963.

On the glacier, the albedo of the snow surface was still very high, thus reducing the effectiveness of incoming radiation in providing heat to the surface, while the heat deficit in the snow pack and ice led to refreezing of most meltwater that might form in the early part of the season. In 1963 (Figure 11) this period ended abruptly when heavy rains between 7 July and 11 July (period 2) washed much of the snow and slush off the surface on the glacier and opened up the meltstreams. Thereafter melting proceeded more rapidly, and after a heavy storm on 20-21 July (period 4) a long period of melt dominance began. During the early part of the season (period 3 and the first part of period 5) the runoff became steadily more heat-sensitive. This reflects three developments on the glacier:

– as the early season heat deficit is overcome, slush begins to form, and drainage com-

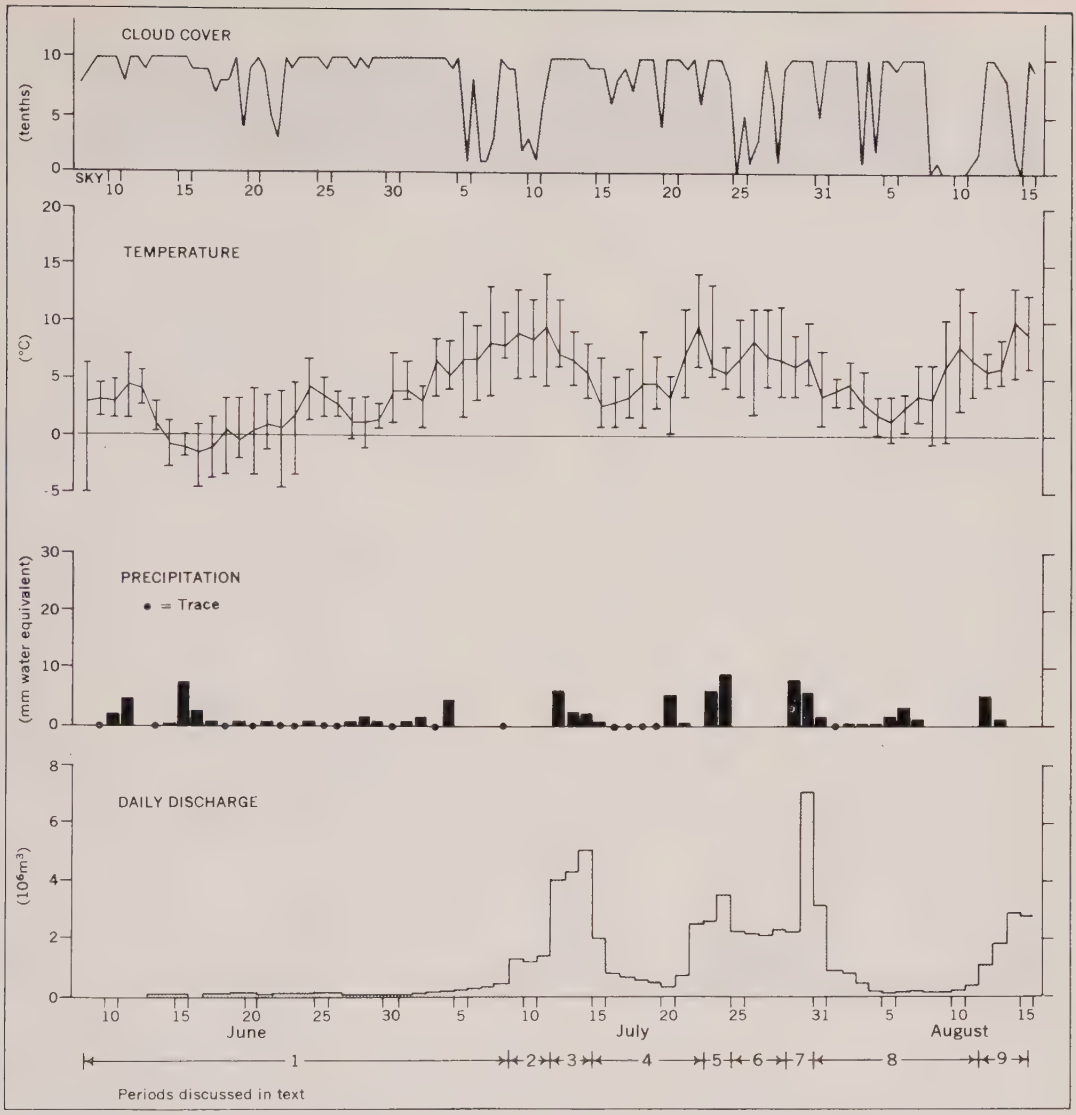


FIGURE 9. Weather elements and stream flow at Lewis station, during the field season of 1964.

mences when the snow pack has become saturated;

– the glacier surface becomes a more efficient absorber of radiation with the lowering of the albedo as the melting of snow and fresh superimposed ice exposes the glacier ice;

– the drainage network of meltwater channels becomes more articulated and extends progressively farther up-glacier so that a greater area of surface contributes actively to runoff.

The rate at which these stages develop depends both on the rapidity with which the mean freezing level rises higher up the glacier with the onset of summer, and on the time at which the drainage channels are "slushed out." In 1963, rain provided a considerable amount of water to accomplish the "slush out" quickly over a considerable area of the glacier.

A state is finally reached in which the entire watershed has become contributary and the old ice surface is reached. Thereafter cumulated melt proceeds in more or less linear relation with the heat index. At the very end of the 1963 season a decrease in watershed sensitivity

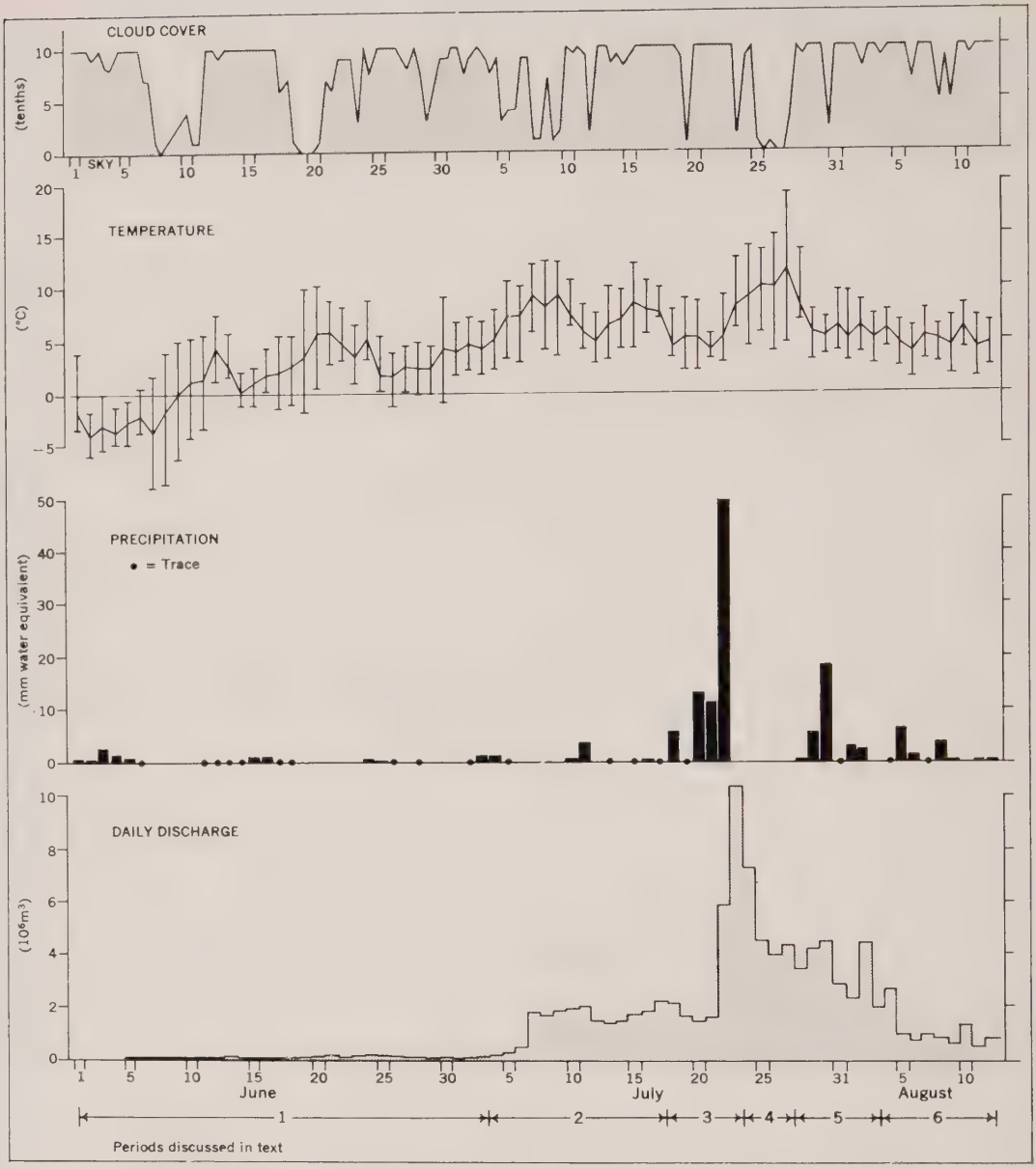


FIGURE 10. Weather elements and stream flow at Lewis station, during the field season of 1965.

was indicated (period 6), presumably after freezing conditions returned and fresh snowfall occurred on the upper areas of the glacier.

In 1964 (Figure 12) the initial "snow melt" period (period 1) ended on 9 July when fine weather triggered extensive slush movement and meltwater channel clearance on the lower part of the glacier. These fine weather conditions continued until 11 July (period 2). Period 3 was characterized by steady rain between 12 July and 15 July, followed by a very cold period with mean daily temperature about 3°C at Lewis station during which melting made little further progress, as seen by the shallow slope of the graph during period 4. Period 5 (20-24 July) was also a rainy period, but this time the heavy rain considerably extended the glacier stream system so that melt-

FIGURE 11. Relation of cumulated runoff to cumulated degree-hours, used as an index of heat supply, for the Lewis watershed during 1963. Each dot represents the cumulated totals at the end of each day; the dashes are trend lines drawn through the dots to indicate periods of essentially linear—that is, similar—glacier response to heating (*i.e*, periods of *constant sensitivity*).

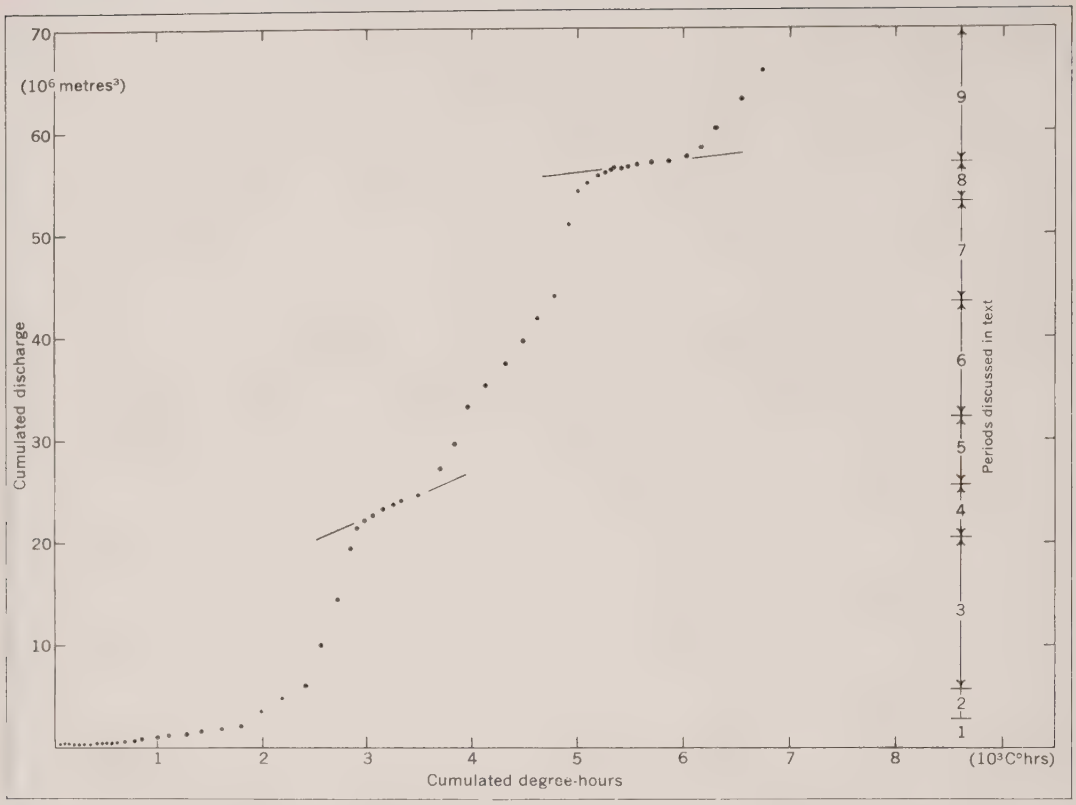


FIGURE 12. Relation of cumulated runoff to cumulated degree-hours, used as an index of heat supply, for the Lewis watershed during 1964. Each dot represents the cumulated totals at the end of each day; the dashes are trend lines drawn through the dots to indicate periods of essentially linear—that is, similar—glacier response to heating (*i.e., periods of constant sensitivity*).

ing proceeded at an increased rate through period 6. This was the warmest recorded period. Heavy rain fell 29 July to 31 July (period 7): very heavy rain during a period of about 6 hours late on 29 July produced a high flood runoff on 30 July, the peak discharge of the season. After this there was a very cold, dull period (period 8). During the early part of this period mean daily temperatures were below 3°C at Lewis station. Virtually no melting occurred on the glacier and thus the effective area of watershed remained very small. Most of the precipitation for 5, 6, and 7 August fell as snow and so no indication of it appears in the runoff record. A return to warm, clear conditions after 8 August failed to influence the very low runoff record to any degree. The watershed remained insensitive to heating, as is reflected in the nearly flat slope of the graph. Period 9 began with rain on 12 August, after which a return to fair conditions began a new period of increased melting.

In 1965 (Figure 13) the initial period of low watershed sensitivity extended until 6 July, when a period of fine weather with relatively high temperatures initiated increased melting and a beginning of the up-glacier extension of the drainage network. The new period of slow but steady melting (period 2) continued until 18 July, though a further period of rain on 10-11 July shows a detectable effect. Between 18 July and 23 July (period 3) heavy rains caused a violent upward jump in the graph of runoff versus degree-days, culminating with 50 mm rain on 22 July, a very unusual storm. These rains greatly extended the drainage network on the glacier as the volume of water slushed out virtually all the channels and carried away most of the remaining snow. Consequently during the fine weather that occurred after 22

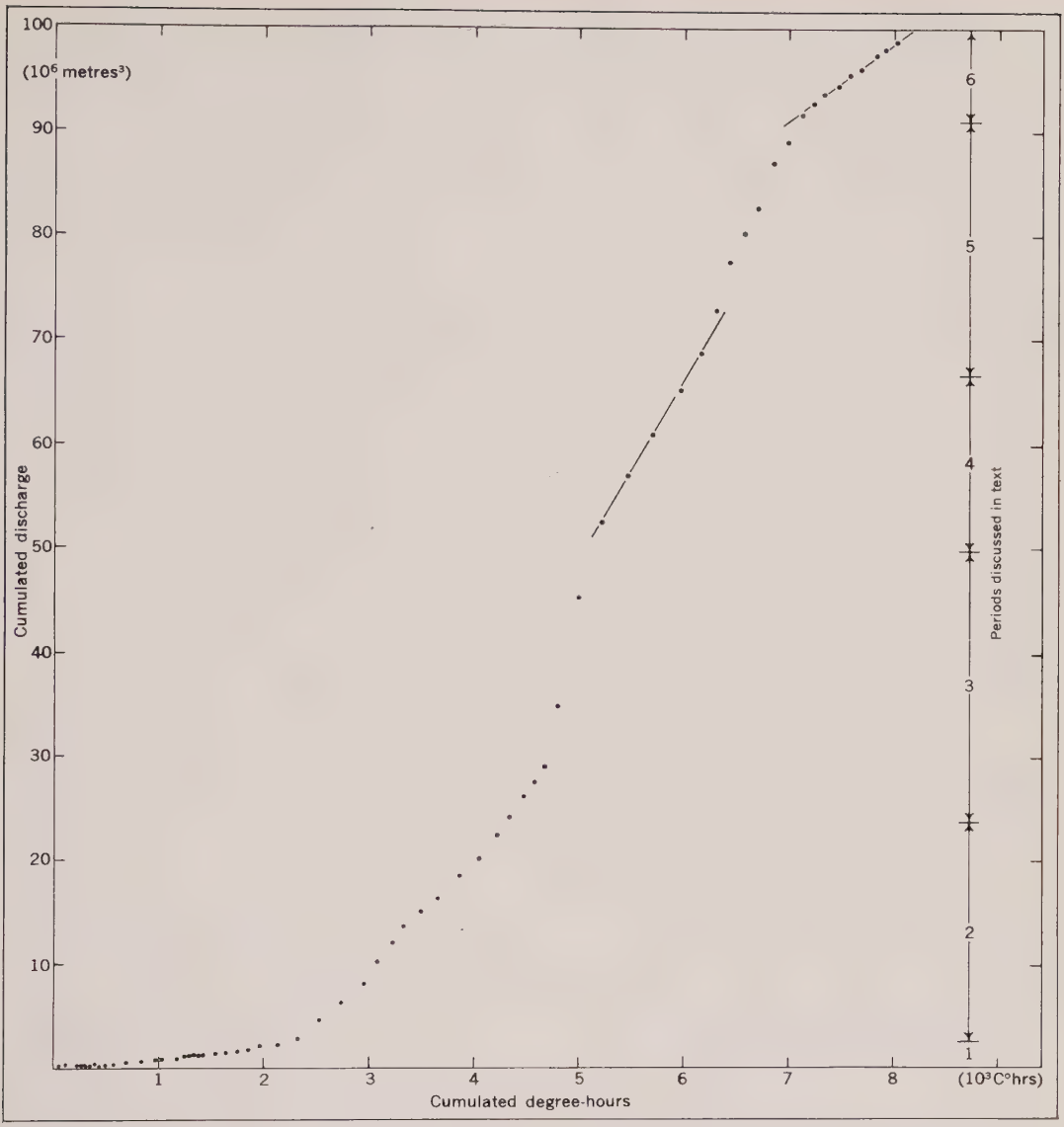


FIGURE 13. Relation of cumulated runoff to cumulated degree-hours, used as an index of heat supply, for the Lewis watershed during 1965. Each dot represents the cumulated totals at the end of each day; the dashes are trend lines drawn through the dots to indicate periods of essentially linear—that is, similar—glacier response to heating (*i.e., periods of constant sensitivity*).

July (period 4) glacier ice melt continued at a greatly increased rate. Storms commencing on 29 July produced further irregular shifts in the pattern of runoff and heating (period 5) though ice melting continued at a considerable rate. However, after 4 August, lower temperatures reduced the melting considerably and so, despite continued storminess, runoff amounts were again much lower (period 6). During this last period night-time temperatures on the glacier fell below freezing, giving a "heat deficit" to be overcome each day, and so the sensitivity of the surface was reduced. By 12 August a light dusting of new snow fell on the upper region of the watershed and drastically reduced surface melting by the abrupt increase in albedo.

The unevenness of the runoff pattern in 1964

and 1965 illustrates another aspect of watershed sensitivity. At very low temperatures, a rise in temperature will not result in a greatly increased amount of runoff since the freezing level lies at a very low elevation below most of the area of the glacier. The watershed cannot respond to the increased temperatures as it would were the freezing level located at higher elevations and is therefore described as *insensitive*. Similarly, at very high temperatures when the entire watershed is contributing to runoff, a further rise of temperature will produce only the increased rate of melt associated with greater heat input everywhere on the glacier and the stable relationship between runoff and degree-hours seen in 1963 will result. It is when temperatures are between these extremes, and when the freezing level lies in the middle or upper portions of the glacier as it did during most of 1964 and 1965, that the most striking changes of runoff with temperature change may occur. At such time even a moderate change in temperature will affect the contributory status of a large surface area.

In this manner the interpretation of the graph of cumulated discharge plotted against cumulated positive degree-hours may be used to interpret the *sensitivity* of glacier watersheds to the weather conditions. Each graph is restricted in application to the watershed for which it is plotted, and no close physical interpretation of the relation between ice ablation and the weather can be gained from it. Nevertheless, for the particular glacier concerned it provides a concise summary of the nature of the runoff and its variation with changes in weather.

SUMMARY AND CONCLUSION

The water budget investigations reported in this paper summarize conditions during three strikingly different years for the Lewis Glacier watershed. The year 1963 was characterized by a high total runoff of 168.0×10^6 m^3 of water, of which about two-thirds was directly due to glacier ice ablation. In 1964, by contrast, runoff measured only 60.5×10^6 m^3 during the period of record and the glacier showed a net gain of mass amounting to 6.3×10^6 m^3 water equivalent. The year 1965 was intermediate between these two extremes, with 99.6×10^6 m^3 runoff being recorded, of which a little over one half was due to ice ablation. Similarly, during the important summer months of July and August, weather conditions in 1965 were intermediate between the relatively warm, dry conditions of 1963, and the cold, wet conditions of 1964, though July 1965 had by far the most rainfall of any month of record.

In 1964 however, a major period of melting occurred after the water budget records were ended, for the net mass balance of the glacier for the entire year, reported in the first part of this paper, showed a net loss of 65.4×10^6 m^3 water equivalent. About 70 per cent of the melt occurred therefore, after 14 August. Nevertheless, the equilibrium line in 1964 lay at 825 metres, indicating a positive net mass balance for the Barnes Ice Cap as a whole. In 1965 the total mass balance showed a net loss of 92.5×10^6 m^3 water equivalent. The summer seasons of both 1964 and 1965 were cool and stormy, and the difference between the two years is largely due to the much greater snow accumulation of the 1964 accumulation season.

An attempt has been made to assess the errors present in the data recorded. The problem is not simple, and in some instances simplifying assumptions and figures of merit which reduce the accuracy of the analysis, have had to be accepted. However, it appears that the mass balance standard error for both years is probably about 12 per cent of the indicated value. The error of runoff composition for the water budget during these years is probably less than ± 17 per cent. While the discrepancy of the water budgets apparently may become quite high, the sustained discrepancy was $+9.0$ per cent in 1963, $+9.4$ per cent in 1964, and -2.5 per cent in 1965. The magnitude of the errors appears to be far more stable than that of the totals observed. Improvements in the rain gauge network and in the snow sampling procedures would most obviously increase the precision of the calculations.

The data for the three seasons indicate that the estimate of the net mass balance from watershed runoff records is relatively reliable only when the mass balance is clearly positive or clearly negative. Near equilibrium the magnitude of the error obscures the results. The method appears to be at least as reliable as direct stake measurements, however. On this basis a 1963 net mass balance has been esti-

mated for the Lewis Glacier at -126×10^6 m^3 water equivalent.

The description of the variations of runoff with weather shows the *sensitivity* of the glacier-dominated watershed to the heat available as the season progresses and melting proceeds on the glacier.

ACKNOWLEDGMENTS

Much of the data incorporated into this report was gathered in cooperation with the Barnes Ice Cap study group led by R. B. Sagar, who also collected the final 1965 ablation data in the spring of 1966. Thanks are expressed especially to M. Church; to C. W. Bridge, C. A. Cherrington, V. Coulombe and C. P. Lewis; to W. F. Rannie and B. Goodison for their assistance in the field; to Dr. G. Østrem, the project director; to Drs. M. Meier, W. V. Tangborn, J. T. Andrews, and O. H. Løken who read the manuscript and made valuable suggestions.

REFERENCES

Adams, W. P.
1962 : A study of some methods of measuring ablation and runoff on an Arctic glacier. Unpubl. M.Sc. thesis, McGill Univ., Montreal.

Andrews, J. T. and Webber, P. J.
1964 : A lichenometrical study of the northwestern margin of the Barnes Ice Cap: A geomorphological technique. *Geog. Bull.*, no. 22, pp. 80-104.

Bauer, A.
1960 : Precision des mesures d'ablation. Abstract on file with the Glaciological World Data Centre A. Am. Geog. Soc., New York.

Hjulström, F.
1955 : The groundwater. Chapter 9 of the Hoffellssandur – A glacial outwash plain. *Geog. Annaler*, v. 37, pp. 234-255.

Hoinkes, H. and Rudolph, R.
1962 : Mass balance studies on the Hintereisferner, Otztal Alps, 1952-1961. *J. Glaciol.*, v. 4, no. 33, pp. 266-278. Discussion pp. 279-280.

Keeler, C. M.
1964 : Relationship between climate, ablation and runoff on the Sverdrup Glacier, 1963. Devon Island, N.W.T. *Arct. Inst. N. Am.*, Research Paper no. 27.

Linsley, R. K., Kohler, M. A. and Paulhus, J. L. H.
1958 : *Hydrology for engineers.* McGraw-Hill, New York, 346 p.

Matalas, N. C.
1963 : Autocorrelation of rainfall and streamflow minimums. *U.S. Geol. Surv.*, Professional Paper 434-B, 10 p.

Meier, M. F. and Tangborn, W. V.
1965 : Net budget and flow of South Cascade Glacier, Washington. *J. Glaciol.*, v. 5, no. 41, pp. 547-566.

Müller, F.
1962 : Zonation in the accumulation area of the glaciers of Axel Heiberg Island, N.W.T., Canada. *J. Glaciol.*, v. 4, no. 33, pp. 302-310. Discussion pp. 310-311.

Østrem, G.
1964 : Glacio-hydrological investigations in Norway. *J. Hydrol.*, v. 2, pp. 101-115.

Sagar, R. B.
1966 : Glaciological and Climatological Studies on the Barnes Ice Cap, 1962-64. *Geog. Bull.*, v. 8, no. 1, pp. 3-47.

Schytt, V.
1962 : Mass balance studies in Kebnekajse. *J. Glaciol.*, v. 4, no. 33, pp. 281-286. Discussion pp. 286-289.

Untersteiner, N.
1961 : On the mass and heat budget of Arctic sea ice. *Arch. f. met. geophys. u. Bioklim.*, v. 12, ser. A, p. 151.

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 262–268, 1967

Notes

FLUVIAL PROCESSES IN THE HIGH ARCTIC

*Frank A. Cook**

ABSTRACT

In the past the erosional role of melting snow in high arctic regions has been generally underestimated. On the basis of quantitative measurements the writer postulates that the intense spring freshet from rapidly melting snow is responsible for the bulk of transport of weathered material, in solution, suspension and by saltation. Rare but heavy rainfalls during the short summer period may also be effective.

RÉSUMÉ

On a généralement sous-estimé dans le passé l'action érosive de la neige fondante dans les régions très septentrionales. L'auteur, s'appuyant sur des mesures quantitatives, considère comme établi que les brusques avalaisons printanières provoquées par la neige fondant rapidement sont les agents de transport de la plus grande partie des matériaux d'intempérisme, tant en solution, en suspension que par charriage. Les averses rares mais fortes de la courte saison d'été peuvent aussi avoir une action efficace.

Many of the smaller streams in the Canadian high arctic flow only during a short summer period of from two to three months. Their regimes are little understood and few quantitative measurements of their runoff characteristics are available. Among erosional processes, however, these streams have local importance. In the past emphasis has been chiefly on the effect of frost action and there has been a tendency to underestimate the part played by stream erosion in the periglacial environment. Recent work in the Canadian Arctic has indicated it may, however, be significant (*see* Robitaille 1959 and 1960; Rudberg, 1963 and 1964, St-Onge, 1962 and 1965). The present note considers the runoff characteristics of the Mecham River near Resolute, Cornwallis Island (Figure 1) and discusses in general terms some aspects of fluvial processes in high arctic regions.

The area considered in this study is arid and is underlain by permafrost to a depth of nearly 1,300 feet, with the active layer thawing to approximately 2 feet during the short summer season (Cook, 1958). These factors combine to provide a rather different role for fluvial action than that which is normal in more southern regions. Few of the standard textbooks take this into consideration.

Quantitative measurements of runoff data were made in 1959 and were supplemented by five summers of qualitative observations and one continuous 15-month period during which the complete yearly cycle was studied. A

*The draft of this note, completed in 1965, was among the papers of the late Frank A. Cook who died in March, 1966. A number of requests for the data contained in the tables prompted the decision to publish it.

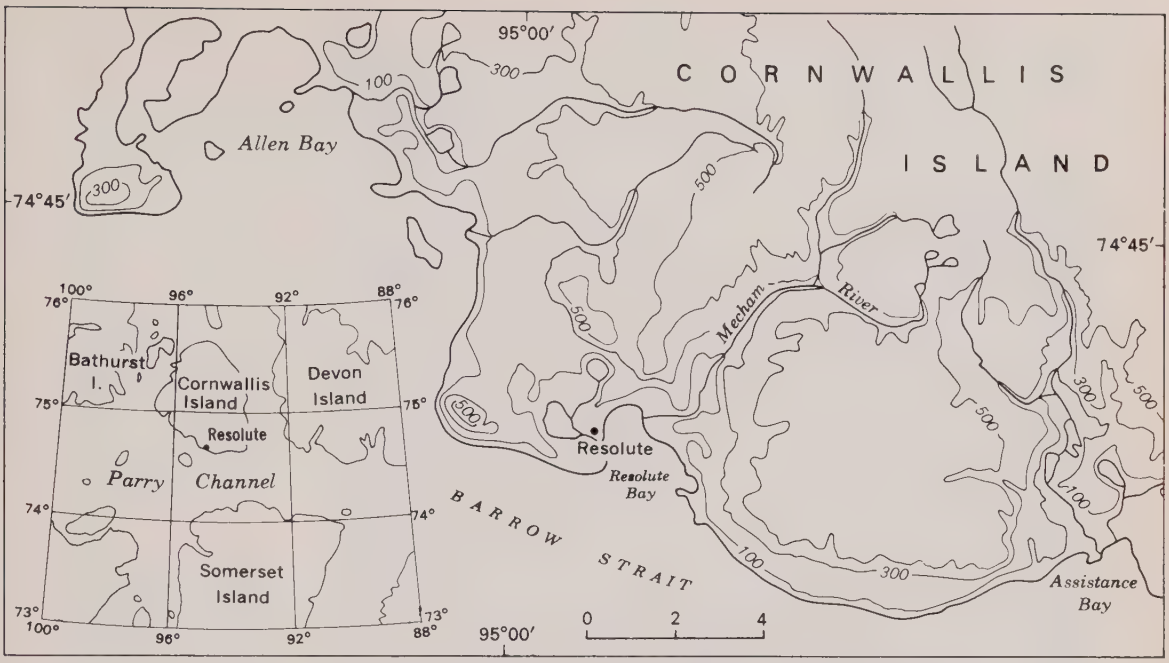


FIGURE 1. Southern Cornwallis Island, N.W.T., showing the course of the Mecham River.

standard current meter was used for measurements, and water velocity – a significant factor in the transport of material was calculated in feet per second. Air and water temperatures were also recorded and observations were made of such other factors as rill-wash and sediment carried in suspension.

The Mecham drainage basin – approximately 10 miles long and with a minimum width of about 5 miles – is incised into the extensive plateau of southeastern Cornwallis Island. In the valley, which is characterized by alternate narrow stretches and wide, flat-floored sections, the Mecham River, a small post-Pleistocene stream eroded into Ordivician and Silurian limestones, is extending rapidly headwards. At its mouth the river cuts through a narrow box canyon to debouch at the head of Resolute Bay (Figure 2). Where the river leaves the canyon, the vertical cliffs and flat rock-ledge bottom provide an excellent site for measurement of stream velocity. Here a control point was established.

The Mecham River runoff is derived from three sources, melting snow, rainfall and the seasonal thawing of the active layer, to list them in decreasing order of importance. No evidence of springs or thermokarst topography was observed.

Snow

As shown in Table 1, snow may fall during any month, the total yearly average being just under 30 inches or approximately 3 inches of water equivalent. Although the high arctic does not experience abnormally high wind speeds, considerable drifting occurs due to lack of vegetation cover. December at Resolute has an average of 12.5 days of blowing snow, the highest total for any month. In the Mecham valley, snow collects in large transverse drifts at the foot of slopes and often completely fills tributary valleys. At the same time, the exposed wind-swept upper slopes and the plateau surface above retain only a minimal cover. Permanent snowdrifts are common in sheltered areas of the valley. Thus, the river's potential runoff from melting snow is appreciably higher than the average snowfall records would suggest.

FIGURE 2
Recording site of runoff observations near the mouth of the Mecham River, September 1959.

*Table I**

Total precipitation, Resolute, N.W.T. 1948-63

	Snow in inches													Rainfall in inches					
Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total	June	July	Aug.	Sept.	Total	Combined total**
1948	0.3	1.3	0.9	0.4	14.6	0.8	—	1.3	8.4	2.8	1.2	0.6	32.6	0.89	0.42	1.20	0.36	2.87	6.13
1949	0.5	1.2	2.3	1.5	1.3	3.2	1.4	2.1	6.4	7.6	1.4	2.4	31.2	0.24	1.78	0.03	0.29	2.34	5.46
1950	1.4	1.7	2.7	1.9	2.8	5.0	T	5.9	9.0	6.8	3.6	0.7	41.5	T	1.38	0.70	0.35	2.43	6.58
1951	0.5	0.8	0.8	1.5	5.0	1.2	0.9	0.7	4.7	5.6	0.7	0.1	22.5	1.60	0.34	0.60	0.03	2.57	4.92
1952	1.2	0.1	2.4	2.5	3.5	0.2	0.5	2.6	5.5	3.8	0.5	3.2	26.0	0.31	0.40	0.60	—	1.31	3.91
1953	T	0.6	0.3	4.4	1.8	5.8	T	T	0.7	5.0	5.1	0.4	24.1	T	0.99	1.70	0.17	2.86	5.27
1954	1.8	1.6	0.6	0.9	3.1	1.0	T	T	2.0	9.3	2.6	1.2	24.1	0.05	1.23	1.18	0.25	2.71	5.12
1955	0.4	1.2	1.0	1.8	0.6	0.4	1.8	5.8	2.5	5.4	3.0	2.4	26.3	0.37	0.95	1.06	—	2.38	5.04
1956	2.6	1.2	1.1	6.3	1.8	0.3	0.5	1.2	2.3	3.5	2.6	0.5	23.9	T	0.74	2.18	—	2.92	5.31
1957	0.5	0.7	0.9	2.3	3.0	1.4	0.6	0.1	6.4	7.4	1.3	1.3	25.9	0.31	0.95	1.76	0.12	3.17	5.76
1958	1.0	1.7	1.5	1.2	2.3	1.7	—	—	6.6	3.8	0.2	1.9	21.9	0.02	1.02	0.11	0.48	1.63	3.82
1959	1.1	1.9	1.0	2.7	3.6	2.0	T	0.1	9.1	9.3	5.2	6.3	42.3	0.20	0.29	0.79	0.19	1.47	5.70
1960	1.3	1.1	0.5	0.6	3.5	1.2	T	T	8.3	10.8	0.7	2.7	30.7	0.14	1.06	2.16	0.11	3.47	6.54
1961	2.6	2.2	0.2	5.7	2.2	4.5	1.0	2.7	7.5	7.4	3.0	3.9	42.9	0.15	1.07	0.19	—	1.41	5.70
1962	0.6	0.2	2.2	0.6	1.3	0.9	0.4	0.5	4.7	3.1	1.6	3.3	19.4	0.15	0.67	0.40	0.05	1.27	3.21
1963	1.2	3.6	1.4	1.0	2.2	2.5	T	5.2	3.3	6.7	3.1	1.7	41.9	0.02	1.03	1.42	0.05	2.52	6.71
Mean													29.8					2.33	5.31

*Reproduced from Cook (1960, Table I) and updated to 1963 from Dept. Transport, Can., Met. Br., records.

**Ten inches of snow being considered equivalent to one inch of water.

In spring, before actual melting begins, a large but undetermined amount of the snow disappears by sublimation. Melting begins before the recorded mean daily air temperatures rise above freezing point for, as previously noted by Cook and Raiche (1962), surface temperatures cross the freezing point up to two weeks earlier than the ambient air temperatures observed in Stevenson screens.

When the mean daily air temperature reaches 32°F, melting is greatly accelerated and, except in a few sheltered areas or permanent snowbanks, the snow in the drainage basin virtually disappears in two or three weeks. The resultant runoff, estimated to be about 90 per cent of the total volume, achieves high velocities and is a significant erosional factor.

Rainfall

Rainfall at Resolute averages less than 3 inches per year (Table 1) and the intensity of individual showers is very low (Table 2). For the 233 days of measurable rain in the 11-year period 1948-1958 inclusive, the average rainfall was 0.12 of an inch. Field observations showed that at least 0.3 of an inch of rain is needed to influence transport of material in the Mecham River although smaller rainfalls can produce some rill-wash. Table 2 shows that nearly 89 per cent of all showers totalled less than the critical amount and, therefore, only on two or three occasions a year will rainfall be an active erosive agent.

*Table 2**

Intensity of rainfall, Resolute, N.W.T. 1948-58

Daily total rain (inches)	Number of days	Percentage of rainfall days in 11-year period	Cumulative percentage
.01–.05	118	50.6	50.6
.06–.10	35	15.0	65.6
.11–.15	24	10.2	75.8
.16–.20	12	5.2	81.0
.21–.25	9	3.9	84.9
.26–.30	9	3.9	88.8
.31–.35	4	1.7	90.5
.36–.40	4	1.7	92.2
.41–.45	3	1.3	93.5
.46–.50	3	1.3	94.8
over .50	12	5.2	100.0
Total	233	100.0	

*Cook (1960, Table 2).

Seasonal thawing of the active layer

This source contributes much less to the total runoff of the Mecham River than does either snow or rain, despite the fact that a considerable amount of water stored in the permafrost is released by the annual thawing of the active layer – which at Resolute reaches a depth of about 25 inches (Cook, 1959).

RUNOFF DATA

It must be emphasized that the runoff data in Table 3 are based on the one parameter of *maximum daily velocity*. Under the conditions involved, these data are more reliable than runoff volume totals which contain many variables and would therefore, possibly show a large margin of error. Relating total runoff to total annual precipitation would present serious difficulties for no accurate measurement of the drainage basin is available, no evaporation studies have been made in the area and, as noted earlier, considerable amounts of snow drift into the basin from the surrounding upland surfaces. Within themselves, however, the data are consistent and give a reasonably accurate picture of runoff characteristics.

The single point measurement method, rather than the average for the whole river cross-section was used. This can give a reading 25 to 50 per cent greater than the average velocity of the total cross-section.

The highest velocity, 12.6 feet per second recorded 30 June 1959 (Table 3) is not inconsistent with the statement that maximum mean velocity of rivers in flood varies from 6 to 10 feet per second (Leopold, Wolman and Miller, 1964, p. 167). At the height of the spate, daily minimum velocities were approximately 30 per cent less than daily maximum velocities.

Quantitative measurements were discontinued 22 July 1959 when the current meter became inoperative and qualitative observations showed a gradual decrease in flow until 10 September, by which date the river had frozen to the bottom. One exception occurred on 9-10 August when a 0.64-inch rainfall was reflected in a sharp increase both in flow and in transportation of material in suspension.

The observed annual cycle of the Mecham River is therefore

– a pre-melt period in early June when snow is lost chiefly through sublimation. Some surface melting may also occur.

– a period of intense melting, lasting perhaps a week, after daily mean air temperatures rise above 32°F. During this period meltwater collects on the valley floor, held back by an ice-jam at the river mouth.

– a period of catastrophic flood following the breaking of the ice jam and the continued rapid melting of most of the snow in the valley. This flood lasts approximately ten days and is estimated to represent about 90 per cent of the total yearly runoff.

– a period of sharply decreased flow which continues until the river freezes to the bottom. Source of runoff during this period is from melting snow-patch remnants, rainfall and melting permafrost. The period terminates before mid-September.

– a period of snow accumulation lasting until June of the next year.

Table 3

Runoff data, Mecham River, June 9 to July 22, 1959

Date	Maximum daily velocity (ft/sec)	Water temperature (F)	Mean daily air temperature (F)	Precipitation (inches)	Remarks
June 9			29 F	0.13	Meltwater observed on top of the river ice which is
10			25	T	frozen to bottom
11			25	T	
12			26	T	
13			25	T	
14			29		
15			29	0.05	
16			35	T	First day mean daily air temperature above freezing
17			36		
18			33	T	
19			33	T	River ice beginning to fracture;
20			33	T	trickle of flow over ice
21			31	T	Ice jam at mouth
22			30	T	
23			32.5		Some flow over ice
24			35		
25			37		Ice jam breaking
26	3.84		39		Ice jam broken — river partly open
27	5.15	33	33.5		River free of ice apart from blocks
28	5.54	33	42		Extremely muddy with much material
29	12.23	33	42.5		carried in suspension and by
30	12.63	33	44	0.15	saltation
July 1	12.33	33	40	0.18	Some rill wash
2	11.74	34	44		
3	10.02	35	39.5	T	
4	6.66	37	39	T	Water becoming clearer
5	6 36	38	43.5		Water translucent to depth of 2 feet
6	1.97	38.5	37		
7	1.80	39	39.5		Water completely clear
8	1.83	40	42	T	
9	2.26	40	36	T	
10	2.16	41	37.5	0.09	Slight muddiness. Note slight in-
11	2.33	39	38	T	crease in velocity due to precipi-
12	1.86	40	39.5		tation
13	1.90	42	38.5	T	
14	2.26	44	40.5		
15	1.15	42	43		
16	1.16	46	44		
17	1.12	45	43.5	T	
18	1.12	41	37.5	T	
19	1.15	40	35.5	T	
20	1.12	40	37.5	T	
21	1.05	40	37.5	0.02	
22	0.95	41	40		Current meter inoperative

In periglacial regions it is difficult to assess the relative importance of the various processes operating simultaneously. Fluvial action is probably ancillary to frost-shattering, solifluction and other forms of mass movement. It is essentially a cathartic, transporting the weathered products of other processes but not, in itself, producing a great amount of erosion. Substantial quantities of material must disappear annually, otherwise valleys would be clogged, and it is postulated that the almost catastrophic spring freshet of melted snow is the main agent of removal for most rock waste. In the main and tributary valleys of the Mecham watershed the writer has observed an accumulation of several hundred cubic metres of blocks and finer rock material, products of frost shattering which had glissaded down the valley slopes on to the river ice. With break-up, much of this debris is ice-rafted out of the drainage system and the rest is either carried away in suspension or moved along the river bottom by saltation. At velocities of 10 or more feet per second large amounts of material can be transported. Some abrasion of the river bottom undoubtedly takes place although, as the bottom remains frozen, the amount is probably slight. On the other hand, the energy produces lateral erosion, especially on solifluction fronts, which may partially account for the seemingly misfit valleys so common in the high arctic.

Heavy rain also produces widespread fluvial erosion and transports considerable quantities of material. However, such rains are rare, occurring at most only once or twice a year, usually late in the summer when the area is very dry and most creeks and rivers have either disappeared or been reduced to mere trickles. Not only may such rains temporarily transform the dry waterways into swollen torrents but they produce considerable rill-wash and develop many exquisite miniature fans and deltas at the foot of slopes (Figure 3) – ephemeral features which disappear with the next spring freshet.

The erosional capacities of ground water from late-melting snow, of seasonal thawing of

FIGURE 3
Fan in the Mecham River valley resulting from a 0.64-inch rainfall August 9-10 in the unusually dry summer of 1959. This single shower accounted for nearly 50 per cent of the year's total rainfall.

the active layer and of rain percolating into the active layer cannot be calculated at present. Carbon dioxide can attain a concentration in snow twenty times greater than in rainwater, and carbonic acid, one of the most potent agents in dissolving mineral salts, produces increased chemical weathering at low temperatures such as would persist under and near snowbanks. Neither the volume of ground water discharged into the drainage basin nor the amount of mineral salts carried in solution is known, but in the limestone area of the Mecham River they may represent a significant factor in the denudational history.

REFERENCES

Cook, Frank A.
1958 : Temperatures in permafrost at Resolute, N.W.T. *Geog. Bull.*, no. 12, 5-18.
1959 : Periglacial-geomorphological investigations at Resolute – 1959. *Arctic*, v. 13, no. 2, 132-135.
1960 : Rainfall measurements at Resolute, N.W.T. *Rev. Can. Géog.*, v. 14, no. 1-2-3-4, 45-50.

Cook, Frank A. and Raiche, V.
1962 : Freeze-thaw cycles at Resolute, N.W.T. *Geog. Bull.*, no. 18, 64-78.

Leopold, L. B., Wolman, M. G. and Miller, J. P.
1964 : *Fluvial processes in geomorphology*. Freeman and Co., San Francisco, 504 p.

Robitaille, B.
1959 : La géomorphologie du sud-est de l'Ile Cornwallis, Territoires du Nord-Ouest. Docteur lettres, Université Laval, Québec.
1960 : Géomorphologie du sud-est de l'Ile Cornwallis, Territoires du Nord-Ouest. *Cahiers Géog., Québec*, no. 8, 359-365.

Rudberg, Sten
1963 : Geomorphological processes in a cold semi-arid region. Reprinted from Axel Heiberg Preliminary Report, 1961-1962 (by F. Müller and others), McGill Univ., Montreal.
1964 : Morphological processes and slope development in Axel Heiberg, Northwest Territories. Nachrichten der Akademie der Wissenschaften in Goettingen. 11-Mathematisch-Physikalische Klasse, Jahrgang no. 14.

St-Onge, D.
1962 : La géomorphologie de l'Ile Ellef Ringnes, Territoires du Nord-Ouest. (Ph.D.) Univ. Louvain, Belgique.
1965 : La géomorphologie de l'Ile Ellef Ringnes, Territoires du Nord-Ouest. Geog. Br., Dept. Mines and Tech. Surv., Etude Géographique, no. 38, 46 p.

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 269–271, 1967

REDUCED VALUES OF SOLAR RADIATION WITH OCCURRENCE OF DENSE SMOKE OVER THE CANADIAN TUNDRA

*James T. Peterson and L. D. Drury**

ABSTRACT

On a reconnaissance flight made on 10 July 1964, dense smoke originating from forest fires in the boreal forest was seen to be transported northward over a wide area of the central Canadian tundra by prevailing southerly winds. Because of the smoke, the average downward solar radiation flux was reduced by as much as 25 per cent.

RÉSUMÉ

Lors d'un vol de reconnaissance effectué le 10 juillet 1964, une fumée dense provenant d'incendies dans la forêt boréale a été vue alors qu'elle était poussée vers le nord au-dessus d'une vaste étendue de la toundra centrale canadienne par les vents dominants venant du sud. A cause de la fumée, le flux moyen descendant du rayonnement solaire a été réduit d'environ 25 p. 100.

During the summer of 1964, the Department of Meteorology, University of Wisconsin, conducted an airborne reconnaissance of the southern boundary of lake ice in north-central Canada (McFadden, 1965). On 10 July 1964, during a flight north and east of Yellowknife, N.W.T. (Figure 1), unusually dense smoke was observed over a wide expanse of the tundra, causing a significant decrease in the amount of solar radiation reaching the ground.

MS submitted August, 1967.

*Mr. Peterson is a Ph.D candidate in the Department of Meteorology, University of Wisconsin. At the time the observations presented here were made Mr. Drury, now on the meteorology staff, United States Army Electronic Proving Ground, Fort Huachuca, Arizona, was also with the Department of Meteorology, University of Wisconsin.

The research reported in this paper was supported by the United States Navy, Office of Naval Research under contract Nonr 1202 (07).

For several weeks prior to this flight, dry weather had prevailed throughout the Great Slave Lake area with Yellowknife recording precipitation of only 0.20 inch in June (27 per cent of normal) and no rain at all for the first twenty-five days of July (Monthly Record, 1964). On July 10, the low-level circulation in the flight area was dominated by a high pressure system centred over the western shores of Hudson Bay. Surface winds of about 15 miles per hour were south to southwesterly. Observed cloud cover consisted of very thin cirrus overcast with occasional narrow bands of stratocumulus.

The smoke originated from a series of rather small forest fires within the boreal forest and was carried northward in slowly expanding plumes which maintained their integrity for at least twenty miles. No build-up of smoke was noted south of the tree line, but immediately

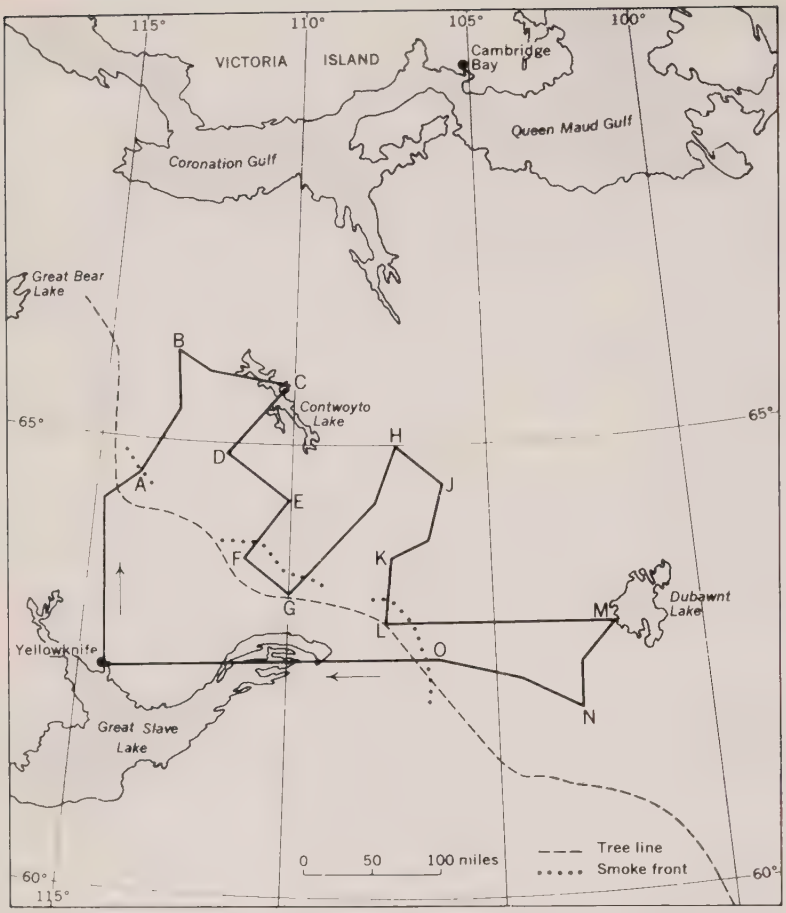


FIGURE 1
Observed smoke front boundary and track of reconnaissance flight made on 10 July 1964.

north of this line the build-up developed abruptly as a wall of smoke extending from the surface to 5,000 feet* with a narrow band of stratocumulus imbedded in the upper leading edge. This general pattern was observed whenever the flight path approached the vicinity of the tree line.

Over the tundra, from west of Contwoyto Lake to Dubawnt Lake, continuous dense smoke was observed, extending at least to 5,000 feet at all times, and on two occasions, to more than 8,000 feet. The northward extent of the smoke was determined from the hourly weather reports at Cambridge Bay, Victoria Island, N.W.T. where smoke was reported in the vicinity by 1600 MST, and by 1700 MST had reduced visibility to six miles.

To investigate the effect of the smoke on the downward flux of solar radiation, data from an *upward-directed* Kipp and Zonen pyranometer aboard the aircraft were used. The pyranometer's measurements of the downward total solar radiation (direct and diffuse) during the flight are shown in Figure 2. The alphabetically labelled vertical lines represent the flight turning points indicated in Figure 1. The abscissa is the 105th meridian time, and the ordinate gives the short wave radiation in relative units. The pyranometer from which the measurements under discussion were obtained was used in conjunction with a similar *downward-facing* pyranometer for the primary objective of albedo measurements. No attempt was made to calibrate the recorder output in absolute terms, although the relative calibration of the two Kipps with respect to each other was known. The recorder output was, however, directly proportional to the input signal, so that the ordinate scale is linear.

*All heights are with reference to mean sea level.

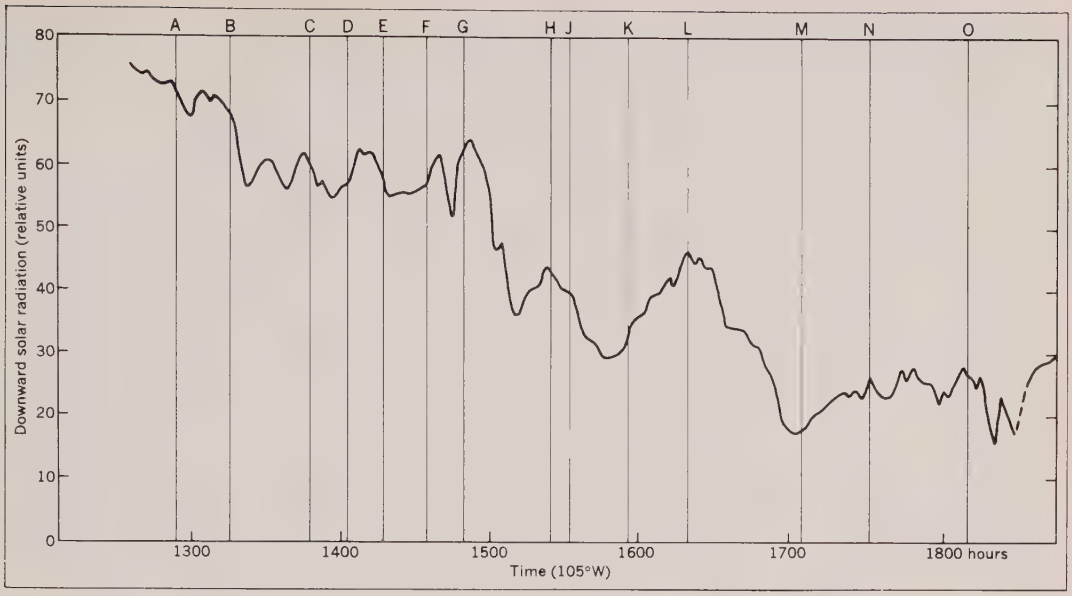


FIGURE 2. Total downward solar radiation as a function of time and location.

Since the density of the smoke increased throughout the afternoon, the flight level was continually lowered to enable observers to distinguish ground features clearly. For example, the flight level was 7,500 feet at *B*, 5,500 feet at *E*, 4,000 feet at *K*, and 2,000 feet at *N*. Just beyond *N* the aircraft rose to 8,000 feet for the homeward journey, which accounts for higher radiation readings in that section of the record.

The attenuation of downward solar flux by the smoke is evident in Figure 2. Higher values were observed in areas generally smoke-free, for example, prior to *A*, at *G* and at *L*, with significantly lower values when the aircraft was in the smoky area. An estimate of the magnitude of depletion of solar radiation was obtained by comparing the readings in the smoke-free areas near *G* and *L* with the values obtained in the smoky region between. Because of the lowering solar angle during the period, two trend lines were drawn through the data, one through the high values at *G* and *L*, representing the possible radiation had there been no smoke, the other through the lower values between *G* and *L*, representing the average radiation actually observed. From the ratio of the magnitude of these lines it was found that at 4,000 feet the smoke caused an average attenuation of 25 per cent in the downward solar flux.

Although high concentrations of smoke over the treeless tundra are not common, the combination of certain meteorological conditions and numerous though not necessarily large forest fires in the boreal forest can cause these to occur. The present measurements were not sufficient to resolve the extinction of radiation into its components of absorption and backscatter, but they showed that the smoke caused a significant decrease in the total amount of solar radiation reaching the ground. This suggests that during periods of drought and accompanying forest fires, the resulting decrease of solar energy should not be neglected in studies concerned with radiation balance climatology.

REFERENCES

McFadden, James D.
1965 : The interrelationship of lake ice and climate in central Canada. Tech. Rep. no. 20, ONR Contract Nonr 1202 (07). Dept. Meteorology, Univ. Wisconsin, Madison.

Department of Transport
1964 : Monthly record of meteorological observations in Canada. Meteorological Service, Toronto.

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 272–283, 1967

USE OF FLOOR SPACE IN THE FUNCTIONAL DIFFERENTIATION OF SMALL TOWNS*

Charles L. A. Hutton

ABSTRACT

Functional variety among small towns and the changes occurring in them are noted; some of the problems encountered in studying them are reviewed. One method of study, found useful in situations where information is scarce and established methodology not entirely applicable, is suggested.

RÉSUMÉ

L'auteur passe en revue la variété fonctionnelle touchant: 1) les petites villes, et 2) les changements qui s'y produisent; aussi, il examine les problèmes relatifs à ces deux éléments. Il propose, comme solution, l'application d'une méthode d'étude sûre et vérifiée là où l'information est peu abondante et où une méthodologie acquise ne convient pas parfaitement.

INTRODUCTION

To geographers, the study of small towns remains largely one of potential. Small centres have not been subjected to intensive study on the scale accorded large cities partly because of the lack of published data but also because they exert comparatively little influence on our way of life. Changes produced by society, on the other hand, often have relatively stronger effects here than they do in large cities. Centralizing tendencies, for example, may in some cases drastically reduce the service areas of many small towns, gradually eliminating service functions which only twenty to thirty years ago were important components of local economies. In other cases, small towns may greatly expand to accommodate overspill from nearby large centres and may acquire new functions as residential or industrial satellites. Occasionally, entire new towns are established. Between these two extreme trends, one leading toward elimination and the other toward expansion, small towns may undergo numerous significant changes which are often shown by shifts in functional emphasis. A number of towns having considerable variety in their functional structure may exist in close proximity.

The more widely known methods of classifying urban centres are based on employment statistics (*see* Harris, 1943; Pownall, 1954; Nelson, 1955; Alexandersson, 1956; Maxwell, 1965). When the present study was begun in 1963, recent employment statistics were not published for towns with populations of less than 10,000. Even now employment statistics are not published for towns of fewer than 1,000 persons nor for most unincorporated centres, though many of the latter have sizeable populations. It is often possible to obtain this information, but of more importance here is

MS submitted June, 1967.

*The work summarized in this paper was carried ou in 1964 as a partial requirement for a Master's degree in geography at the University of Alberta, Edmonton, Alberta.

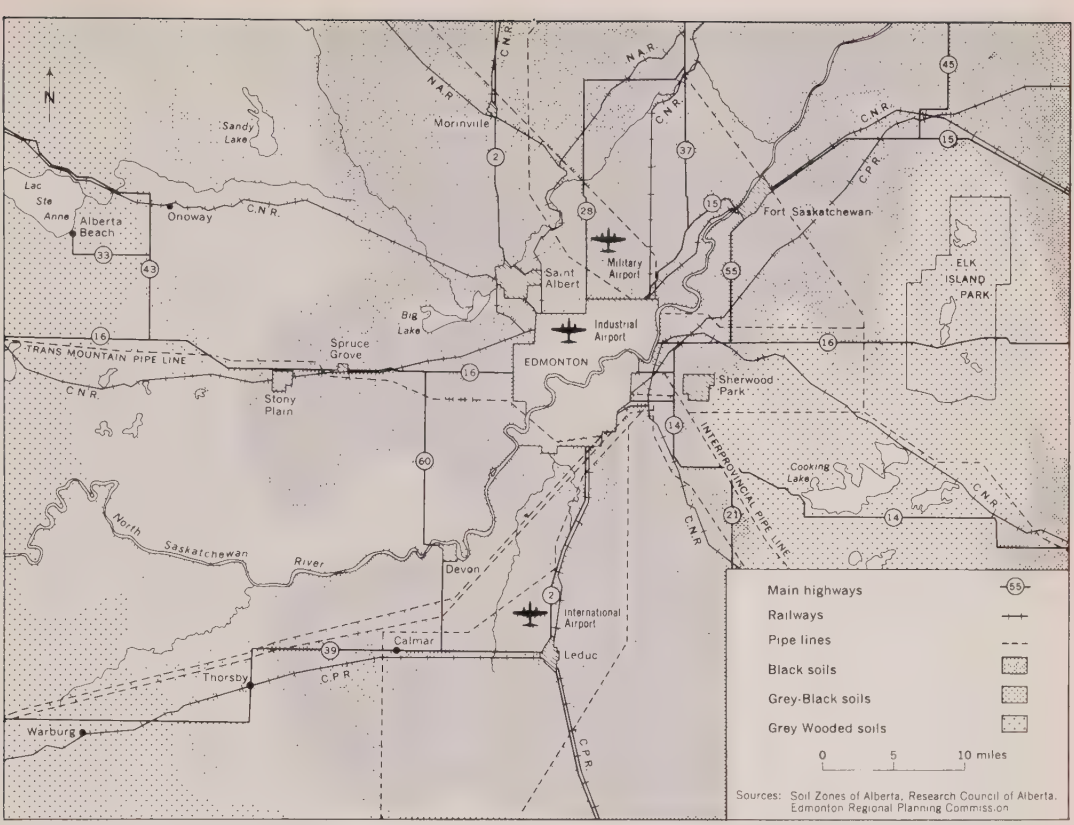


FIGURE 1. Area around Edmonton, Alberta, showing the eight towns studied for functional comparison and their location relevant to transport routes and the regional soil zones.

the fact that an increasing number of smaller communities are assuming a satellite function which greatly distorts their employment structure relative to the census since workers are usually employed in large metropolitan areas nearby. Use of trade statistics is often prevented by disclosure rules, and other indices of urban functions – income, man-hours of labour or value of production – introduce difficulties of their own since many functions like those performed in schools, hospitals, churches, homes for the aged, and community recreation centres are extremely difficult to assess in these terms, even if data were available. In short, a new method of classifying small towns and comparing their functional structures is needed to overcome problems resulting from lack of published data, peculiarities of satellite towns, and the many urban functions not easily classified in common economic terms.

This paper outlines a method used to classify and compare the functional structures of eight small towns in the Edmonton area: Devon, Fort Saskatchewan, Leduc, Morinville, Spruce Grove, Stony Plain, Saint Albert and Sherwood Park (Figure 1). All are situated within twenty miles of Edmonton in a region where change has been particularly rapid and widespread during the last twenty years and where the towns exhibit a variety of functional types. The method yielded useful results in cases where only limited published data were available and where established methodology was not completely applicable.

METHODOLOGY

Towns reflect their various functions in the number, type, size and location of buildings. For purposes of this study it was postulated that the amount of floor space occupied by

various functions such as retailing, manufacturing, construction and administration could give some indication of basic functional variation among towns. Floor space data for nearly all buildings in the study towns were readily available from assessment files in town offices. It was reasonable to assume that if floor space were related to population, a set of ratios could be derived which would serve as a statistical index of functional variations. For example, the floor space-population ratios derived for dormitory communities which lack the economic base to employ all their residents could be expected to differ widely from the ratios for service centres which possess facilities in excess of those required by the towns themselves.

Classification of functions

Floor-space data were classified according to function, using a system adopted by the Dominion Bureau of Statistics in its *Standard Industrial Classification Manual* (1960). Nine of the functional categories listed in the manual occur in the study towns and have been used for Table 1.

The towns studied were considered to be functional rather than political entities; if facilities clearly functioning as part of a town were situated just outside the corporate limits, they were included, (*see* Fort Saskatchewan Figure 5). Data were collected for all types of floor space except residences and farmsteads. Residences were excluded since there is little variation among towns in per capita occupancy

Table 1

Total non-residential floor space in study towns – May 1964
(All floor space figures are in square feet)

Category		Devon	Fort Sask.	Leduc	Morinville	Spruce Grove	Stony Plain	Saint Albert	Sherwood Park	Average
*Population**		*1,423*	*3,766*	*2,846*	*1,000†*	*596*	*1,466*	*8,583*	*4,830‡*	
Agriculture	Floor space		5,622	2,222	18,916		2,235			
	Percentage of town total		0.5	0.5	7.6		0.6			1.2
Mines, Quarries, Oil Wells	Floor space	62,211		7,393				3,920		
	Percentage of town total	24.1		1.6				0.6		3.3
Manufacturing	Floor space	3,036	566,884	13,912	8,400	8,110	9,602	4,618	850	
	Percentage of town total	1.2	51.3	3.0	3.8	7.9	2.4	0.7	0.4	8.8
Construction	Floor space	7,063	3,936	4,351	896	1,079	600	22,294		
	Percentage of town total	2.7	0.4	0.9	0.4	1.0	0.1	3.5		1.1
Transportation, Communication, Utilities	Floor space	13,365	10,106	19,635	6,343	3,206	10,272	15,946	2,760	
	Percentage of town total	5.3	5.2	0.9	4.2	1.3	3.1	2.6	2.5	2.6
Trade	Floor space	34,589	100,968	114,888	74,788	45,785	134,642	77,955	31,380	
	Percentage of town total	13.4	9.1	24.8	30.2	44.6	33.4	12.2	15.1	22.9
Finance, Insurance, Real Estate	Floor space	3,816	7,302	5,323	2,687	1,446	3,071	4,770	1,995	
	Percentage of town total	1.5	0.7	1.1	1.1	1.4	0.7	0.8	1.0	1.0
Service Industries	Floor space	125,887	217,205	270,524	107,319	40,827	223,686	486,600	165,246	
	Percentage of town total	48.8	19.5	58.4	43.3	39.7	55.6	76.1	79.6	52.6
Public Administration, Defence	Floor space	7,701	193,303	25,277	27,341	2,341	18,547	22,959	5,460	
	Percentage of town total	3.0	17.5	5.5	11.0	2.3	4.6	3.6	2.6	6.3
Total		257,668	1,105,326	463,525	247,690	102,794	402,655	639,062	207,691	

*May, 1964 — local census.
†Estimate from Town Office — May, 1964.
‡Estimate from Sherwood Properties Ltd. — May, 1964.

of housing; farmsteads were omitted because their floor space performs a non-urban function. In Table 1, compiled floor space data is indicated for the functional categories in each study town. It becomes apparent that the towns with larger populations do not necessarily have correspondingly more floor space in any category. Further, not every category is represented in each town, the smaller towns and residential satellites generally having fewer functions.

In the *Agriculture* category the amount of floor space occupied is small, partly because of the system of classification. Agriculturally related establishments such as dairies, poultry processors, and feed and flour mills are all classed as manufacturing rather than as agricultural industries, and grain elevators are included with other storage and warehousing industries in the broad category of *Transportation, Communication, Utilities*. All floor space in the *Mines, Quarries, Oil Wells* category is either directly involved in, or associated with, the oil and gas industry. Though there are no truly large manufacturing enterprises except in Fort Saskatchewan, the *Manufacturing* category is a diverse one and representative segments of it appear in each town. The *Construction* category shows limited floor space because of its comparatively specialized nature and by the fact that much of its activity is carried on outdoors. *Trade* is a major function of each town and in Spruce Grove it constitutes the largest floor space category. In most of the other centres it ranks second in size only to the extensive *Service Industries* category. Due to its specialized function, the *Finance, Insurance, Real Estate* category is small in all towns, but it is relatively uniformly represented, occupying about one per cent of the floor space in each town. The largest single category is *Community, Business, Personal Service Industries* (shown as *Service Industries* in the Tables) which is consistent with the fact that in a broad economic sense most of these towns are basi-

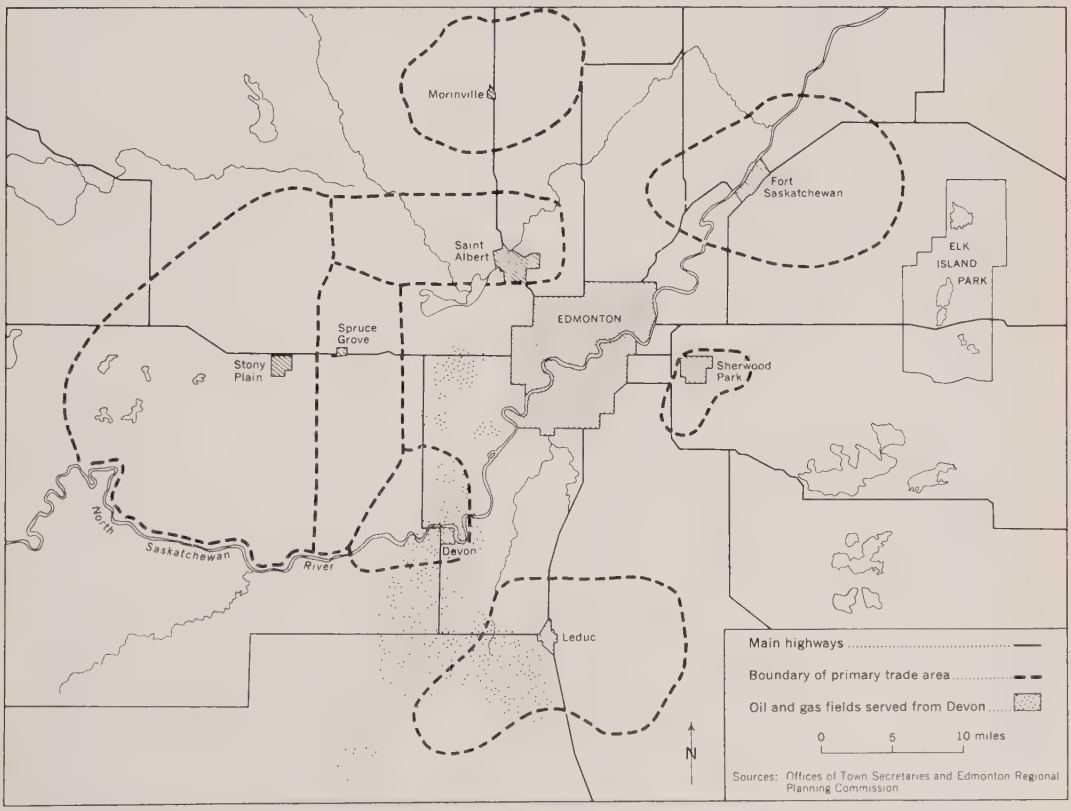


FIGURE 2. Economic service areas of the eight small towns in the Edmonton area studied for functional comparison.

cally service centres (Figure 2). Approximately 12 per cent of the floor space occupied by this category is used for commercial service industries – cafes, hotels, bowling alleys and barber and beauty shops – while the balance is used for various public service establishments like schools, churches and hospitals, many requiring extensive floor space. The *Public Administration, Defence* category includes facilities used by all levels of government: federal, provincial, municipal and local. Fort Saskatchewan, Leduc and Morinville show relatively high floor space totals in this category because of extensive facilities occupied by non-local governments.

Only one deviation from the Dominion Bureau of Statistics classification was made; an oil company office building in Devon was classed in *Mines, Quarries, Oil Wells* since the offices were concerned with the production of crude oil rather than with the manufacture of oil products.

Classification of study towns

Each town was classed according to its functional structure using the ratios summarized in Table 2. Although the main functions can be noted by simple inspection of the towns, and the *size* of a function relative to that of another town can be seen from the floor space totals in Table 1, it is the *ratios* (in comparison with those of other towns) that emphasize the degree of functional significance or *dominance*. The ratios (Figure 3) also reflect interrelations among functional categories noted during field work.

The number of high ratios in the *Service Industries* category indicates that most of these towns are basically service centres. Since numerous large public buildings are included, high ratios can be expected. As it involves functions common to most towns, this category was generally ineffective as a differentiating factor, though in Saint Albert and Sherwood Park its high proportion of total floor space and its corresponding high ratios were indicative of a residential satellite function (Tables 1 and 2).

Figures 4 to 8, compiled by fieldwork, illustrate land use and the distribution of functions in each town.

From secondary high ratios in Table 2 and Figure 3, which reflect more distinctive functions, the towns were grouped into four types: *Devon* was classed as an *Oil Town* (Figure 4); *Fort Saskatchewan* a *Manufacturing Town* (Figures 5 and 6); *Leduc, Morinville, Spruce Grove* and *Stony Plain* were classed as *Trade Towns* (Figure 7). The last four towns are more strongly oriented to surrounding trade areas than are the others and function broadly as agricultural service centres. As already mentioned, the low over-all ratios for Saint Albert and Sherwood Park and their high proportions of floor space in the *Service Industries* result from the dominant residential character of both towns and reflect the relative scarcity of commercial functions. Both are classed as *Residential Satellites* (Figure 8).

Comparison of the ratios in Table 2 with published employment data is presented in Table 3. Though obvious gaps occur and cate-

Table 2

Floor Space ratios (in square feet per 100 persons)

Category	Devon	Fort Sask.	Leduc	Morinville	Spruce Grove	Stony Plain	Saint Albert	Sherwood Park	Average
Population	*1,423*	*3,766*	*2,846*	*1,000*	*596*	*1,466*	*8,583*	*4,830*	
Agriculture		149	78	1,892		153			284
Mines, Quarries, Oil Wells	4,372		260				46		585
Manufacturing	213	15,053	489	940	1,361	655	54	18	2,348
Construction	496	105	153	90	181	41	260		166
Transportation, Communication, Utilities	939	268	690	634	538	701	186	57	502
Trade	2,431	2,681	4,037	7,479	7,682	9,184	908	650	4,381
Finance, Insurance, Real Estate	268	194	187	269	242	209	56	41	183
Service Industries	8,847	5,768	9,505	10,732	6,850	15,258	5,669	3,421	8,256
Public Administration, Defence	541	5,133	888	2,734	393	1,265	267	113	1,417
Total	18,107	29,351	16,287	24,770	17,247	27,466	7,446	4,300	18,122

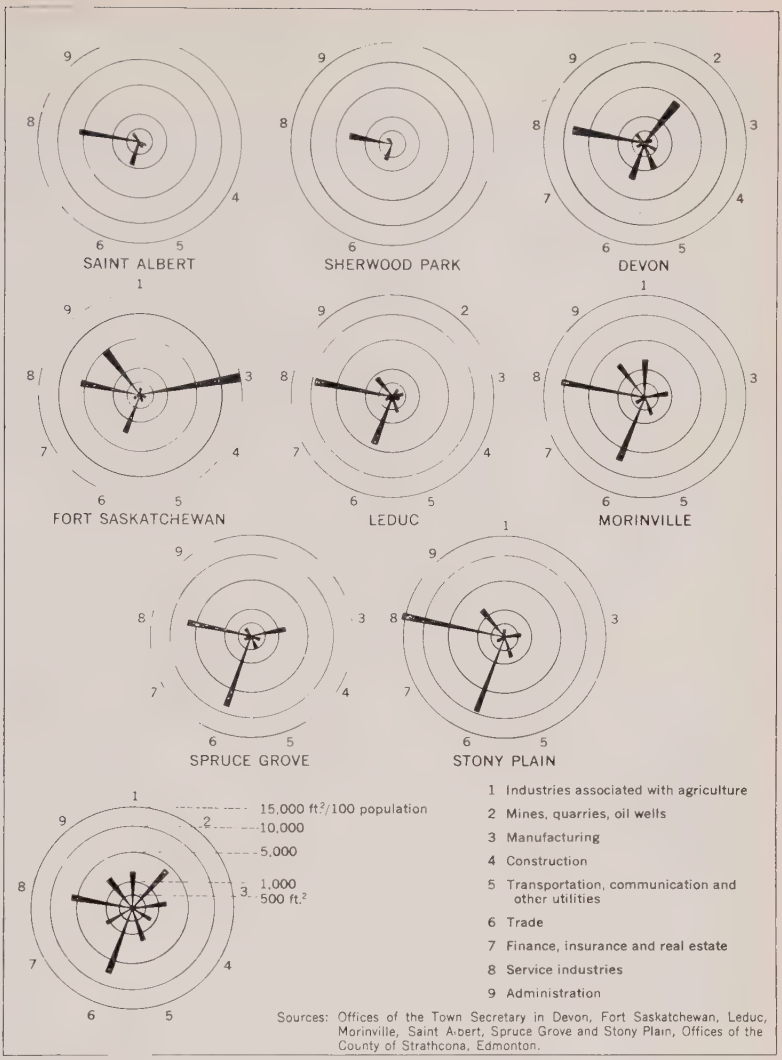


FIGURE 3
Town functions expressed in floor space ratios.

Table 3

Occupations

Occupation	Devon	Fort Sask.	Morinville	Leduc	Spruce Grove	Stony Plain	Saint Albert	Sherwood Park
*All Occupations**	*495*	*939*	NO PUBLISHED DATA	*748*	NO PUBLISHED DATA	*431*	*1,279*	NO PUBLISHED DATA
Managerial	44	95		96		64	140	
Professional and Technical	56	142		58		54	191	
Clerical	38	96		83		34	150	
Sales	21	37		43		38	102	
Service and Recreation Occupations	60	128		80		56	188	
Transport and Communication Occupations	31	21		75		57	90	
Farmers and Farm Workers	6	23		31		10	31	
Loggers and Related Workers	—	—		2		—	—	
Miners, Quarrymen and Related Workers	111	2		35		4	12	
Craftsmen, Production Process and Related Workers	71	342		181		87	291	
Labourers	39	26		47		21	53	

*Includes persons not reporting occupation.

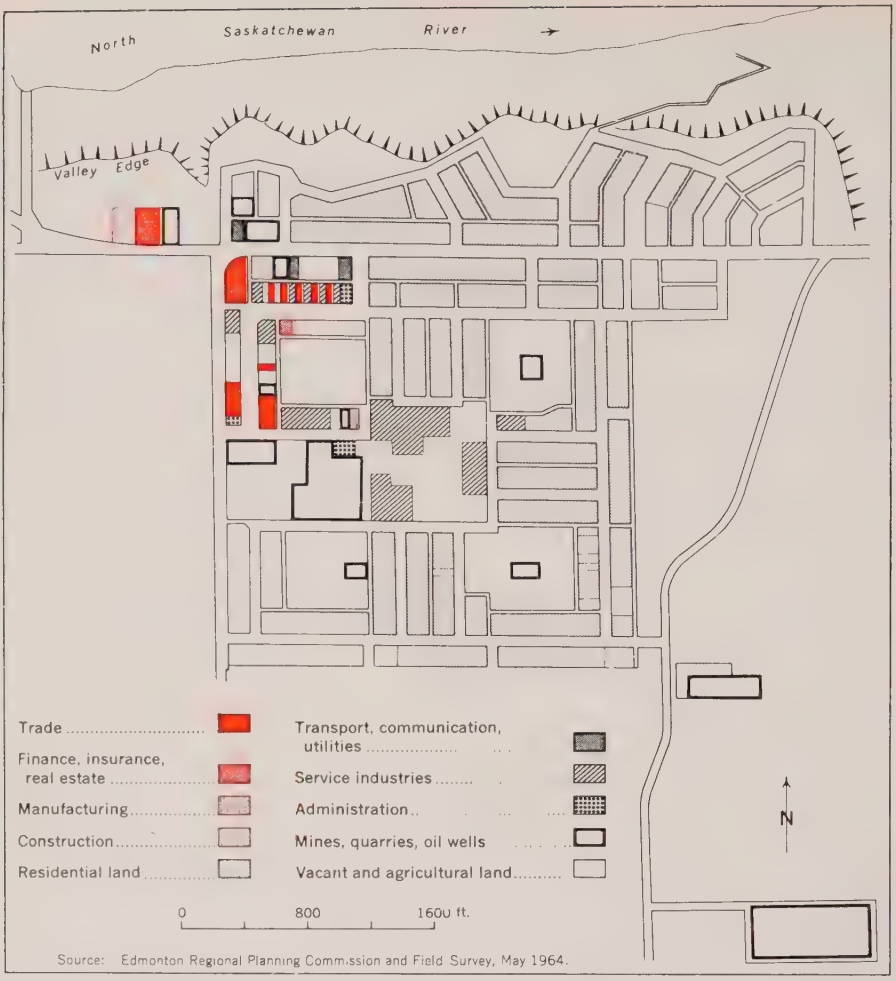


FIGURE 4. DEVON, land use (pop. 1,423).

gories differ, enough similarities occur – with the notable exception of Saint Albert – that Table 3 is in rough general agreement with the ratios shown in Table 2.

The Oil Town (Figure 4)

Devon, one of the few completely planned communities in Canada was laid out and settled between 1947 and 1949 as a central service town in the new Leduc-Woodbend oilfield. After the peak period of drilling and development work, the primary function became routine oilfield servicing and maintenance. By 1954, population had reached equilibrium at between 1,400 and 1,500.

The largest single industry and most distinctive function is well expressed in a high ratio in *Mines, Quarries, Oil Wells,* but carries across into two closely related categories (*see* Figure 3). Oilfield trucking firms contribute to a high ratio in *Transportation, Communication, Utilities,* while pipe line and oilfield contractors enlarge the *Construction* ratio. These are the only activities in which Devon functions as a regional commercial service centre.

The comparatively low ratio in the *Trade* category reflects both the lack of an agricultural service function and the scarcity of other specialized retail and professional service outlets. Devon was built at a time when the need for a close network of rural service centres had decreased, and previously existing centres,

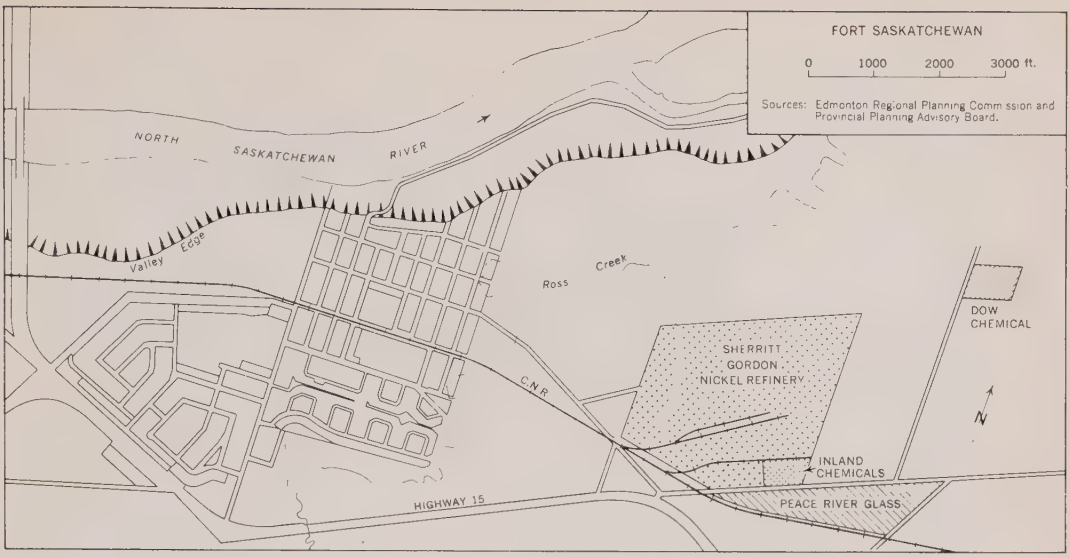


FIGURE 5. FORT SASKATCHEWAN, townsite and location of out-of-town industrial sites.

notably Edmonton, continue to dominate in the regional supply of most specialized goods and services.

Manufacturing Town (Figures 5 and 6)

Fort Saskatchewan, long an agricultural service centre and the location of a provincial jail, acquired extensive industrial development when a large nickel refinery and fertilizer plant – requiring a dependable water supply, rail facilities for ore shipment and great quantities of natural gas – was located there in 1952. Since then, other industries, mainly chemical producers, have aided the town's transformation into a manufacturing centre. The population which had become stabilized at about 1,000 persons between 1916 and 1952, reached a new equilibrium of approximately 3,800 by 1954.

Reflected in Fort Saskatchewan's singularly high *Manufacturing* ratio, the larger industries in 1964 employed 810 workers, including 177 who commuted from Edmonton. The high *Public Administration, Defence* ratio is due to the presence of the jail. Despite their high ratios, the potential effects of these industries on the town are somewhat reduced since supplies and services are frequently obtained from Edmonton or other more distant points. Commercial competition from Edmonton is felt in many functions and has had a direct effect in keeping the *Trade* ratio low. Although the well established agricultural service functions continue to operate, expanded commercial facilities resulting from the recent population increase were not built as extensively as forecast. Between 1953 and 1961, while population increased by 120 per cent, the value of retail sales increased by only 64 per cent. Although Fort Saskatchewan has the types of functional categories common to the other towns, the physical extent and relative significance of the facilities are reduced by the above factors and low ratios result.

Trade Towns (Figure 7)

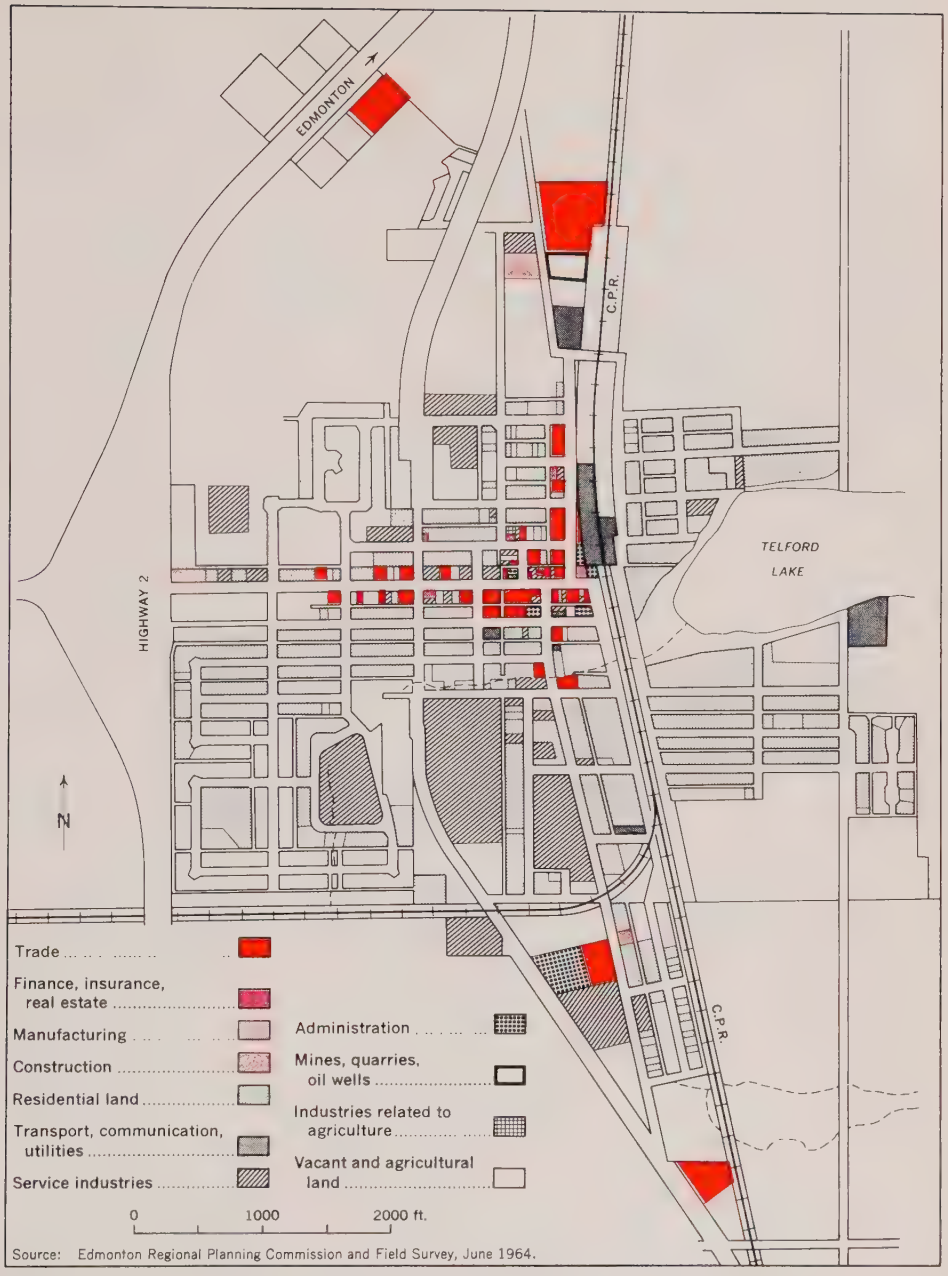
Trade is an important function in all of the study towns, but in Leduc, Morinville, Spruce Grove and Stony Plain it has special significance as shown by the high floor space ratios in this category (*see* Table 2 and Figure 3). This is the functional class, which serves as the best single indicator of a broad agricultural service function. Other categories also involved in agricultural service are *Agriculture, Manufacturing,* and *Transportation, Communication, Utilities.* The four trading towns have generally high ratios in these categories. In addition, they have storage capacity for approximately 1,000,000 bushels of grain, 75 per cent of the total for the eight towns studied. Nevertheless, regional centralizing trends have the effect of

FIGURE 6. FORT SASKATCHEWAN, land use. (pop. 3,766).

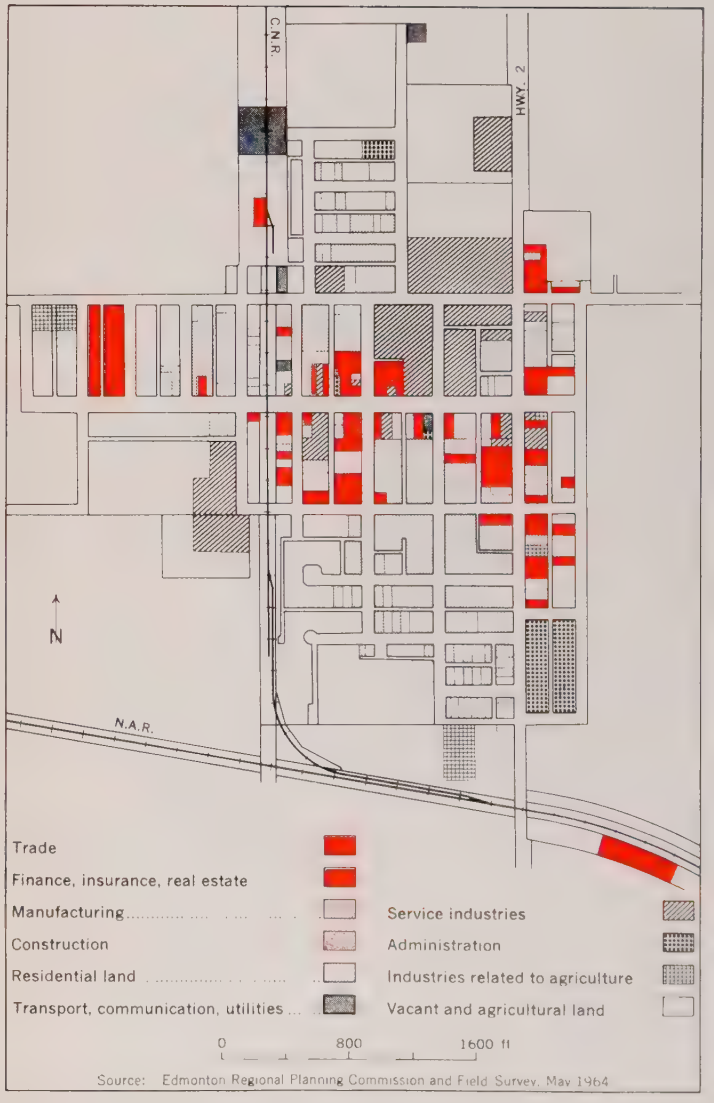
keeping the level of the ratios suppressed since Edmonton is a major supplier of goods and services for these towns and their trade areas, and some of their utilities systems are integrated with those of the city.

Leduc

Like Edmonton and Devon, Leduc was much affected by oil development in the late 1940s and early 1950s, but to a lesser extent. In 1951, the population levelled off at near 2,100 per-

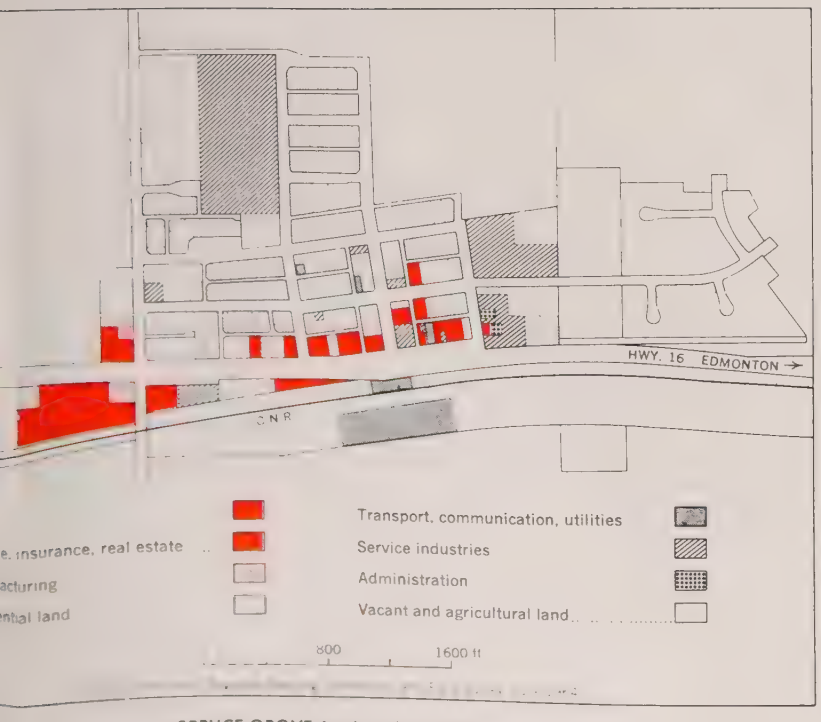


LEDUC, land use (pop. 2,846)



MORINVILLE, land use (pop. 1,000)

OWNS



SPRUCE GROVE, land use (pop. 596)

STONY PLAIN, land use (pop. 1,466)

sons, double the 1946 figure, which had expanded gradually from 112 in 1901. In 1959, it began increasing once again due to construction of the Edmonton International Airport nearby and it now stands near 3,000, exceeding the population of its primary trade area by almost 1,000.

Since the late 1940s the relative significance of the agricultural service functions has decreased and the *Trade* ratio is now substantially lower than those of the other *Trade* towns. Most of Leduc's other ratios are also likely to remain low as its functional structure develops a stronger residential emphasis.

Morinville

During the last 20 years, Morinville has grown more gradually than most of the other study towns and remains strongly dominated by its agricultural service functions. The primary trade area, supporting a population roughly equal to that of the town, is the main factor contributing to a high *Trade* ratio, an above-average ratio in *Transportation, Communication, Utilities* and a relatively high ratio in *Manufacturing*. The high ratio in *Agriculture* is due to a fur farm.

Spruce Grove

Spruce Grove, an agricultural service centre of 600 persons was established about the same time as Stony Plain but failed to match Stony Plain's growth. Located only 17 miles from downtown Edmonton, Spruce Grove is beginning to be affected by urban "overspill", as shown in the development of new residential subdivisions. Its specialized function is reflected in high ratios in *Trade* and *Manufacturing*. The main manufactured products are farm animal feeds. The town's small size is reflected in the lowest *Service Industries* ratio of any of the four *Trade* towns.

Stony Plain

Like Morinville, Stony Plain ratios have not been reduced by the influxes of new population so characteristic of the other study towns during the last 20 years. Prior to 1946, development paralleled that of other agricultural service centres in the region; population increased relatively steadily from 505 in 1911 to approximately 1,500 in 1964. The grey-wooded soil zone west of the town (Figure 1) supports a rural population more sparse than that surrounding the other towns. There is no centre of comparable size for a distance of 40 miles to the west. Consequently, its primary trade area (with a population of 2,500) is the most extensive and Stony Plain has the most diversified commercial facilities of any town in the study group. Its *centrality* and specialized functional structure are strongly reflected in very high ratios in *Trade* and in the *Service Industries*.

Residential Satellites (Figure 8)

Saint Albert, established as a mission in 1861, is one of Alberta's oldest towns. Its population in 1890 was about 1,000, 90 per cent of Métis origin. By 1901, Métis were no longer so numerous and the recorded white population was 472. The town gradually grew to 1,320 persons by 1956, functioning mainly as a religious and agricultural service centre. Population then jumped to more than 9,000 by 1966, largely because of proximity to the rapidly expanding city of Edmonton. Development of commercial facilities has been much slower than population growth as 80 per cent of the labour force is employed in Edmonton. Both facts contribute strongly to the generally low ratios in Table 2. The only category in which Saint Albert has a higher than average ratio is *Construction,* resulting from the fact that, from 1960 to 1963, the value of building permits issued far exceeded that of any other study town. Even so, the *Construction* ratio is minimized by the town's proximity to Edmonton since city firms have been the main contractors. The relative significance of agricultural service functions has been much reduced by urban population growth while the rural population has either remained steady or declined slightly. In 1961, the population of the primary trade area was approximately 1,000 and business competition from Edmonton was strong.

Sherwood Park

Low as Saint Albert's ratios are, they are nevertheless higher than those of Sherwood Park, a gradually expanding urban centre established in the mid-1950s and having a population of 5,000 in 1961. Also like Saint

Albert, 80 per cent of the labour force is employed in Greater Edmonton and commercial development has been much slower than population growth. Unlike Saint Albert, Sherwood Park had no previously existing urban functions before its rapid population growth occurred. The commercial facilities that now exist are not primarily concerned with serving a trade area; they serve only the local population. In comparison with the other towns, its floor space ratios indicate the almost complete lack of a local economic base. If Saint Albert is a residential satellite of Edmonton, Sherwood Park functions as a detached suburb.

DISCUSSION

Comparisons of town functions based on the floor space technique were used only between corresponding functional categories of different towns, not between categories in the same town. Floor space does not necessarily reflect the entire significance of an urban function if only one town is considered. For example, since much of the construction industry occurs outdoors, minimal floor space is used and the ratio of floor space to population is not directly comparable with that of the retail trade. When construction floor space ratios of different towns are compared, however, significant differences become clear.

If these ratios were to be applied over a large enough region, variation due to climate would likely be encountered, particularly with industrial facilities. In this case, perhaps the ground area physically covered by the installations could be considered instead of only the enclosed floor space. Care should be taken to separate space in short term temporary use, such as outdoor storage, from that in permanent use.

In data collection, some inconsistency was encountered in cases where the basis for tax assessment was not floor space but storage capacity by the bushel or by the gallon. With facilities like grain elevators and oil storage tanks, neither measure is readily convertible to floor space information. Possibly the data would be more useful if expressed in terms of cubic content of structures rather than in square feet of floor area. Variations in the size of some single-floor buildings, such as grain elevators and churches, could then be taken into account and the system could directly include any type of enclosed structure such as oil tanks or ore storage facilities. For most facilities in the study towns this information was obtainable from assessment files, but for some it was not. It is doubtful if the added complications that would be encountered in obtaining this information from scattered sources would yield a correspondingly improved functional analysis. Further, most buildings in towns of the size studied are relatively small and have a similar basic relationship between volume and floor space. In these cases, floor space served as a reasonable common denominator for placing various facilities on a comparable level.

No distinction was made on the basis of cost, intensity of use or economic return; floor space in use twenty-four hours a day was given the same consideration as space used only eight hours. Introduction of an additional factor based on value or intensity of use would again lead to unnecessary complications; for example, storage space in use twenty-four hours daily is used less intensively than retail sales floor space used only eight hours a day and both are quite different from manufacturing space in use twenty-four hours a day in three working shifts.

CONCLUSIONS

Although the ratios are most easily understood when used with supplementary information on building permits, population change, trade and service competition, they offer an effective way of measuring and comparing the functional structures of towns. Most of the required data are readily available. The method is equally applicable to both commercial and non-commercial functions and takes into account facilities in the *Service Industries* category such as churches, clubs, homes for the aged and schools for the retarded, which are not directly revenue producing and are not readily measured in purely economic terms of investment, sales volume, value of output or man hours of labour. The method is more useful than employment statistics for satellite towns. It is inherently objective in approach, presenting no necessity for the subjective "weighting" of data entailed in other procedures (*see,* for example, Harris, 1943).

On the limited scale undertaken here, the

use of this method for differentiating space in a study of urban functions has been illustrated and a test made of its value as a means of classifying small urban centres. A further test could involve direct comparison with other methods of functional differentiation, preferably in an area where town functions are not as clearly dominant as in the eight study towns. If a broader application were attempted, a useful approach might involve a hierarchial ranking of urban centres, or comparisons of the ratios of individual towns with regional or national averages.

ACKNOWLEDGMENTS

Generous assistance from public officials in gathering basic data is gratefully acknowledged: Mr. L. Abrams, Strathcona County offices, Edmonton; Mr. B. D. Stover, Devon; Mr. J. A. Clark, Fort Saskatchewan; Mr. W. A. Bell, Leduc; Mr. L. U. Brochu, Morinville; Mr. S. L. Billings, Saint Albert; Mr. T. C. Gamble, Spruce Grove and Mr. E. Pink, Stony Plain.

REFERENCES

Alexandersson, G.
1956 : *The industrial structure of American cities.* Univ. Nebraska Press, Lincoln, 134 p.

Dominion Bureau of Statistics
1960 : *Standard Industrial Classification Manual.* Queen's Printer, Ottawa, 287 p.
1963 : Labour Force, Bulletin 3.1 - 8, *1961 Census of Canada.* Queen's Printer, Ottawa, Table 14.
1963 : Population, Bulletin 1.1 - 10, *1961 Census of Canada.* Queen's Printer, Ottawa, Table 6.

Harris, C. D.
1943 : A functional classification of cities in the United States. *Geog. Rev.*, v. 33, no. 1, 86-99.

Maxwell, J. W.
1965 : The functional structure of Canadian cities: A classification of cities. *Geog. Bull.*, v. 7, 79-104.

Nelson, H. J.
1955 : A service classification of American cities. *Econ. Geog.*, v. 31, 189-210.

Pownall, L. L.
1954 : The functions of New Zealand towns. *Annals Am. Assoc. Geogr.* v. 43, 332-350.

Data relevant to this study are also contained in the following publications:

Edmonton District Planning Commission
1954 : *A general plan for Fort Saskatchewan.* Edmonton, 36 p.
1955 : *A general plan for the Town of Leduc.* Edmonton, 35 p.
1956 : *A general plan for the Municipal District of Stony Plain.* Edmonton, 39 p.
1957 : *A public works program for the Town of Morinville.* Edmonton, 43 p.

Marlyn, F. and Lash, H. N.
1961 : The Edmonton district. A city centred multiple resource region. *Resources for Tomorrow.* Queen's Printer, Ottawa, v. 1, 455-470.

Smith, P. J.
1962 : Fort Saskatchewan: An industrial satellite of Edmonton. *Plan Canada*, v. 3, 4-16.

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 284–293, 1967

EARLY SETTLEMENT ABOUT MEDICINE HAT, ALBERTA

*R. Common**

While the prosperity of Medicine Hat is usually associated with the fortuitous discovery and use of a cheap supply of natural gas, discovered by accident in 1883 when Canadian Pacific Railway workmen were searching for a section water supply at Alderson, the growth and development of the city have been determined by a number of other physical and human factors, the relative importance of which has changed over the years.

Located within the Alberta section of Palliser's Triangle and at a considerable distance from other settlements of comparable size, the city represents an island of urban humanity in the sparsely populated, short grass plainland (Figure 1). Suffield and Redcliff are the only other agglomerated settlements of any importance for, apart from service type hamlets at Dunmore, Seven Persons and Bowell, there is only a thin peppering of dispersed rural settlement in the area. To live successfully in this distinctive part of the Prairies people in all these settlements have had to adjust their perspectives, values and habits to a spacious and fickle physical environment as well as to changing economic and social conditions.

MS originally submitted May 1966.

*Dr. Common is a member of the Geography Department, The Queen's University, Belfast, Northern Ireland.

Editor's note

This informal account of the early years of Medicine Hat has been included in this issue of the *Geographical Bulletin* as it provides some background interest of the area in and around the Cypress Hills where the Geographical Branch has conducted climatological, pedological and geomorphological research for several years. The text contains no internal referencing but a short general bibliography is appended.

Initial development

The original site of Medicine Hat was determined by particular circumstances in 1883, for until the arrival of railway construction workers the river side does not appear to have held any permanent attractions for either native or white people. Although a river terrace site was used by the Crees during the hunting season, the only resident in the area was the half-breed trader Roderick Ross, who, in 1875, had settled nearby at the creek which now bears his name. Explorers like Palliser had passed the site by, while the North West Company and Hudson's Bay Company trading posts were established elsewhere in the Saskatchewan basin at what were considered to be more advantageous riverside locations — the confluence of the Red Deer and South Saskatchewan rivers and the junction of the Old Man and Belly rivers. Even those traders from the United States who preferred seclusion for some of their activities, shunned this locality. The only native encampments recorded by Palliser lay well to the north. Others, of uncertain date, are now inferred from tipi stone-circles located during fieldwork near Drowning Ford, 23 miles downstream. Because the more favourable physical conditions on the higher ground to the south offered a timber supply to the Indians and a strategically placed control point to the Northwest Mounted Police, the early overland trails

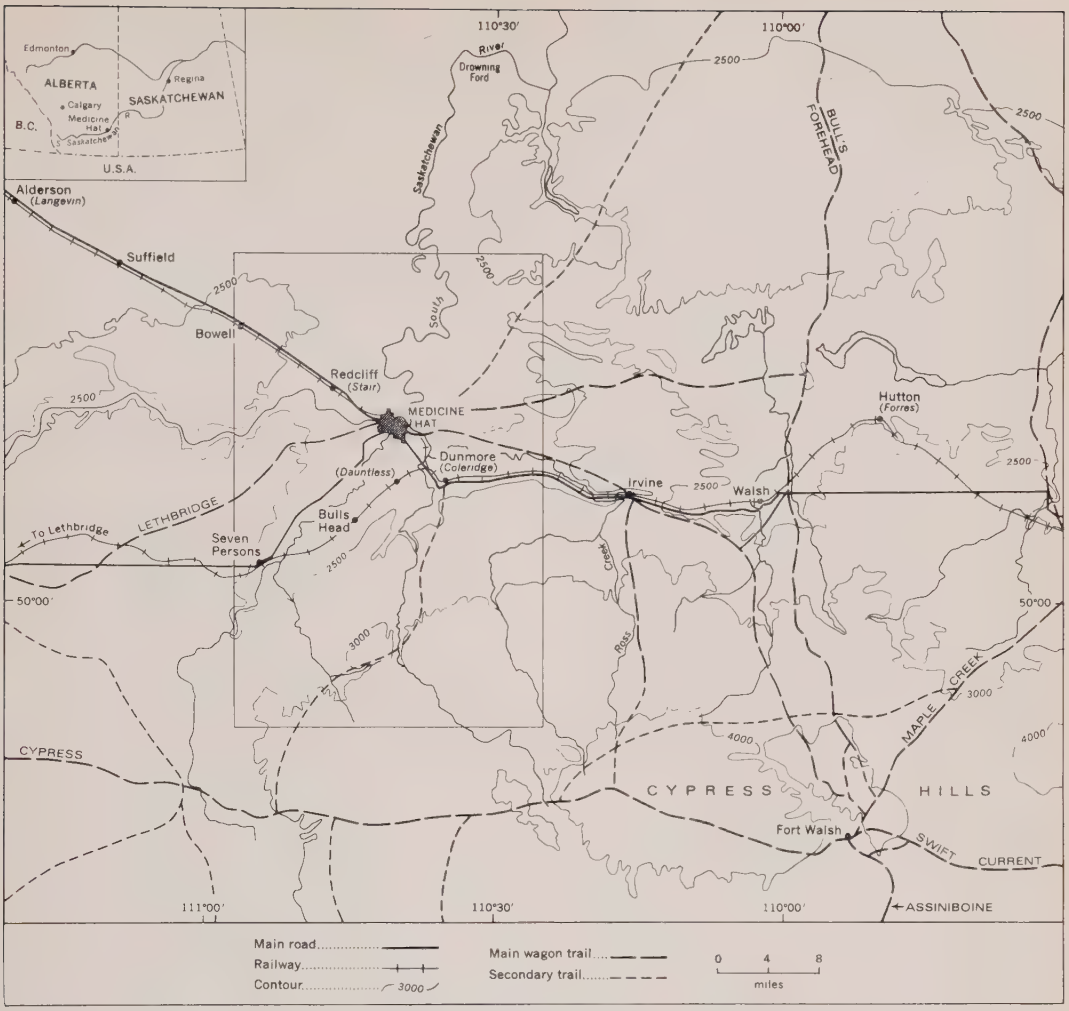


FIGURE 1. The area of early settlement around Medicine Hat. Place names in italics indicate either settlements which have disappeared or names which have become obsolete. The 800-square mile area around Medicine Hat enclosed within the rectangle is specifically referred to in the text.

also bypassed the site of Medicine Hat, crossing the South Saskatchewan River only at easily forded points to converge upon the Cypress Hills.

The naturally graded, flat floor of Ross Creek must have seemed a providential solution to the railway men's problem of which way to turn once they quitted the glacial spillway that had brought them as far as Dunmore. It also led to an assured supply of river water, cottonwood or poplar trees for construction purposes, and outcrops of workable coal seams nearby. Beyond the local low, terraced banks of the river the regional gradient of the relief increases westward toward the Rocky Mountains and the suitability of this easy bridging point must have been apparent to the railway men, although Morrow (1923, p. 18) records that the railway bridge site was fixed farther upstream than originally intended, because of questions of title. Only about a dozen persons anticipated the arrival of the railway track by several months, but they were joined before the end of 1883 by about two hundred others.

The establishment of a bridge, ferry and railway depot, marked the first phase of settle-

ment on the south bank of the river. Also in 1883, a 55-man detachment of the North West Mounted Police from Fort Walsh established permanent camp on the north bank, just east of the railway bridge. Their intention was to discourage any illicit traffic in whisky, to reduce the risk of horse stealing and, if need be, to "show the flag" when the railway was pushed through Blackfoot country. In 1885, because of the unsettled political conditions centering around Louis Riel and the Métis, troops arrived in the area from Fort Macleod and Halifax.

Meanwhile the early settlers were chiefly occupied with the railway, coal and the land. They lived in railway box cars, in log cabins made from local cottonwood or in tents set up on lands that had still to be officially surveyed. The few Cree families who drifted into the vicinity camped apart and to the east of the railway track on the lowest terrace, now known as "The Flats". In 1883, squatters began sod-breaking for cereal and root crops in the even-numbered land sections of T15, and R6*. They also grazed 1,100 head of cattle. In the same year two Experimental farms were established at Dunmore and Stair by the C.P.R. Of these, the Dunmore farm produced the most promising crop yields with wheat giving 20 bushels per acre, oats 38.8 bushels per acre, barley 32.5 bushels per acre and peas 10.3 bushels per acre. Maize and garden vegetables were also introduced and successfully ripened on both farms. In 1885 and 1887 the Canadian Agriculture and Coal Colonization Company acquired land in the same vicinities for settlers, but by 1888 both these colonies had become preoccupied with stock rearing. Local newspapers give credit to James Sanderson, for bringing cattle and horses down to Medicine Hat from Fort Walsh and it therefore seems likely that crop and animal husbandry developed simultaneously in the area. There seems little doubt that the available game resources were soon drawn upon to supplement the food supply of these pioneers, for the numbers of deer and antelope were depleted and the few remaining plains buffalo eliminated.

By 1885 Medicine Hat had grown to the proportions of a village in which church and school were both represented and the services of a doctor, a carpenter and a lawyer were also available. The first store was established in 1883 to serve the railway construction crews and by 1884 South Railway Street boasted a modest frontage of two hotels, four stores, two bakeries, a drugstore, dressmaker and brewery. Drilling within the city took place in 1891 and proved a supply of wet gas but dry gas, in abundant supply, was not tapped by deep bores until the beginning of the present century.

Within fifteen years the population had increased to about 1,000 persons and the settlement had been officially incorporated as a town. The buildings, now on surveyed land, were set out within the standard rectangular street framework and the community possessed a number of churches, recognized school facilities, a hospital and a newspaper. Local interest in placer deposits had flared up momentarily, only to die down because of the poor returns for the labour involved. Not until 1928 would fresh dredging leases again be taken out and then only for a series of short term tests on the Saskatchewan alluvial deposits. Farming of arable land continued to develop uneventfully but ranching, which had spread out from the Fort Macleod and Cochrane centres, really became significant locally after 1890, due to the results achieved by the Mitchell Brothers. Ranching regulations in the late 19th century stipulated that the lessee after securing location should place and maintain at least one head of stock for every 10 acres of his holding within two years and a nominal rent of 2 cents per acre was to be paid annually.

Competition for Land

Although early proposals for the establishment of a meat canning industry in the building of a small woollen company at Medicine Hat were soon abandoned, individuals and companies continued to acquire large ranches and grazing leases about the South Saskatchewan River and on the Cypress Hills. In 1902, for example, the Western Packing Company of Winnipeg acquired 1,400 acres and leased another 16,000 acres of grazing land and the

*The Dominion Land Survey divided the Province into square townships of 36 square miles and these were numbered northward from the International Border. The location of townships was provided by Range numbers, measured westwards from the 4th meridian (*i.e.*, 110 W). Medicine Hat thus lies in T12 and R5.

Seeley Hammond ranch, when sold in 1907, contained 740 acres, with leases on another 1,280 acres. Considerable numbers of cattle, horses and sheep were reared, grazed and shipped eastward by rail in these early days (Table 1) and by 1910 conditions had been sufficiently favourable for pure breeding stock to be imported from overseas. That same year however, the rising demand from other sources for the available land forced the Western Stockgrowers Association to press the Dominion Government for greater security of leases and grazing rights in order to protect the ranchers' interests.

Table 1

Stock Shipments in 1910

Shipment point	Horses	Cattle	Sheep
Medicine Hat	2,396	776	1,375
Dunmore	421	4,311	4,630
Bulls Head	6	2	—
Seven Persons	6	3	—

A second group competing for land in the area was composed of land companies. Within the various settlements they "boosted" the real and fictional attributes of lots in order to create completely artificial values, and because of the speculative optimism of the times their salesmanship was often extraordinarily successful. Early in 1910, for example, the surveyed town site of Suffield, laid out on bald prairies but expected to become the thriving centre of an irrigation district, was offered for sale. Within three days $24,000 worth of lots, each 25 by 130 feet, were reported to have been sold at prices ranging from $50 to $350 per lot.

In Redcliff the *raison d'être* for the settlement was essentially one person's initiative. In 1906, Dr. Stoner bought the Stair farm and because of his interests in a land company, he quickly sold much of it. Clay deposits in the gullied, riverside portion had already proved suitable for brick-making and, since there was also a local supply of coal, Dr. Stoner quickly organized the Redcliff Brick and Coal Company. With the local discovery of a natural gas supply prospects brightened still further. A townsite astride the spur line from the main C.P.R. track to the new brick plant was surveyed and by 1910 lots became available for purchase in the nascent settlement.

Although the true boom period in real estate lasted from 1908 to 1913, the habit of "boosting" began earlier and has continued sporadically ever since. Fortunately, sufficient financial, human and physical resources were available to sustain most of the initial industries attracted to Medicine Hat and a premature withering of the settlement was avoided. Less fortunate, in this respect, were the nearby centres of Suffield, Bowell, Redcliff, Seven Persons, Dunmore and Coleridge, which are now merely reminders of "what might have been." The only example of a hamlet which completely failed is provided by the foundations of Dauntless, five miles south of Medicine Hat. Established with a cement factory, it lived and died between 1910 and 1920.

The third group to make extensive inroads into the available land was the homesteaders (Figure 2). They trickled in comparatively slowly prior to 1908, but once land regulations were improved, and the Department of the Interior Land Agency Office began to function in Medicine Hat, their numbers swelled considerably. They used freight cars to transport their effects to railway halts conveniently near their property. Montana ranchers and Dakota crop farmers were among the early American arrivals, but later, individuals from as far apart as Madison, Wisconsin and Holmesville, Nebraska also filed for the available land. British, Germans – either individually or collectively in religious sects – Scandinavians and Russians immigrated into this countryside (Figure 3), as did Canadians from already established centres on the Prairies and from British Columbia in the west to Prince Edward Island in the east.

Complaints on the abuse of homestead land, demand for more homestead land and pressure from other claimants led to the establishment of the land agency office which was to serve the district centred on Medicine Hat (R1 to R10, T1 to T23 inclusive). Besides dealing with the available homestead land, this office realistically sold off both filed land where no effort had been made to pay taxes, and reserved land unlikely to be developed for schools. The disposal of land by this land agency office in 1911 is shown in Table 2.

FIGURE 2. Homestead entries in the Medicine Hat area to 1911 (data from records of the Department of the Interior). Marginal medians are adjusted to township survey corrections.

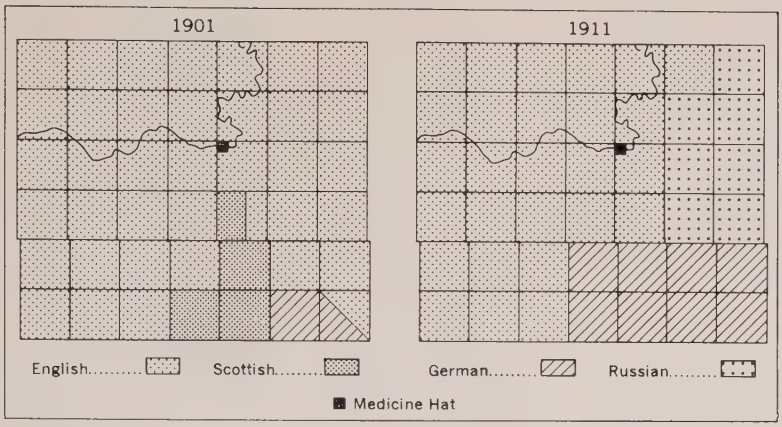


FIGURE 3
Predominant origins of the population shown by township and quarter section.

Table 2

Entries during 1911, in the Medicine Hat area

Homesteads	2,894
Preemptions	1,865
Purchased homesteads	120
Scrip	271
Acreage involved	5,500,600

GROWTH OF SETTLEMENT AND POPULATION

In the 800 square miles around Medicine Hat (enclosed within the rectangle outlined on Figure 1) applications for 452 homesteads were entered prior to 1908, but in the three years following, 197, 194 and 117 entries were made. During this period the grassland of the Great Plains was being fenced, as shacks, framehouses, barns and tents were proliferating in those tracts of land most accessible to the railway. A variety of crops was grown, including extensive areas of wheat, oats and barley as well as garden cultivation of pumpkin, marrow, tomato, squash and potato. By 1910 this list has been further extended by the introduction and successful growth of flax, rye, sugar beet, turnip, maize and alfalfa. Nevertheless, several of the less desirable aspects of the local climate had already been experienced in these early years, such as hail, drought and the erratic spring floods of the South Saskatchewan River, which severely damaged property on "The Flats" in 1902 and 1909. Not until 1910 were hail insurance policies available to the farmers and not until 1911 did the Dominion Government agree to provide seed grain to those homesteaders who had suffered drought failures in the preceding year.

The population of Medicine Hat grew from 300 in 1885 to about 900 in 1895 to 1,500 by early 1901, and to 5,608 in 1911. Early ties between the settlement and the railway were first maintained and later strengthened to the mutual benefit of both parties. The original railway depot was built in 1885 for the operation of four freight and four passenger locomotives but it was not until 1911 that the social and economic development of the community persuaded the C.P.R. to develop Medicine Hat into a divisional point and the terminus for the Crows Nest Branch line. This decision not only meant the establishment of workshops, freight yards and a roundhouse capable of holding fifty locomotives in the central part of town, but also provided employment for additional shop workers, track maintenance men and train crews. Local newspaper records suggest that 50 men were to work in the shops and 45 on track maintenance, while 66 train crews were to be based at this depot. The railway served the needs of the community by maintaining a demand for fuel and by its transport of coal and ceramic clay to and from local centres. In addition it provided the only effective means of long-distance traffic into and out of the area.

Early ties with Lethbridge were largely due to the initiative of the Galt family who first sought a C.P.R. contract for the coal from their mines. For supply purposes stern-wheel river steamers and barges were built, and based

on Lethbridge and Medicine Hat, but they quickly proved difficult and uneconomical to operate. Nothing daunted, their owners then constructed a narrow gauge railway track – "The Turkey Trail" – from Lethbridge to the C.P.R. line at Dunmore, as an alternative route. But with 400,000 acres of disposable land at the Lethbridge end, this rail line offered more than simply an outlet for coal. Within ten years this track had been relaid and was then leased by the C.P.R. who finally bought it outright in 1897.

When the possibility of Medicine Hat developing into a focal transportation point was realized by the more optimistic members of the community, irregular attacks of "railway fever" began. In 1912, for example, it was seriously considered that the local station could be used by not less than seven different railway companies operating in Alberta, Saskatchewan and Montana. This optimism concerning railway possibilities characterized the first thirty years of this century, and resulted in the spasmodic buying and selling of land considered potentially useful for track development.

Prior to World War I progress in the other forms of transportation was either ephemeral or lethargic. The town's brief connection with the river as a highway terminated in 1908 after the home-built *City of Medicine Hat* sank at Saskatoon and the local river ferry had been replaced by a traffic bridge. Away from the railway, overland travel remained dependent upon the horse and wagon, so that horse bazaars and/or livery stables were very much a part of the scene in all the settlements.

Between 1906 and 1914 local resources and capital from various sources were used to establish industries, the products of which could either be sold locally or marketed elsewhere at competitive prices. Supplies of ceramic clay suitable for bricks, building-tiles and sewer pipes were first utilized intensively after 1907, with the building of brick and pottery plants at Medicine Hat and Redcliff. Success in this venture encouraged an increase in the range of products manufactured and the number of plants in Medicine Hat. However, as the industry expanded, local clay deposits became depleted and supplies were first brought by rail from near Dunmore and, more recently, hauled by truck from the Cypress Hills.

Again, the relatively long frost-free period, permissive microclimatic factors on the lower river terraces and the availability of cheap fuel supplies were all favourable to horticultural enterprise. These considerations, coupled with imaginative appreciation of market demands and the services of the railway, encouraged local and Winnipeg capital to be invested in land and greenhouses for the growing of flowers and vegetables.

The growing volume of agricultural production and the increasing numbers of homesteaders in the district were soon reflected in new functions within the city. Flax, which had proved to be a successful crop, represented a source of linseed oil for a paint industry and a cash crop to the farmer; both opportunities were served with the building of a linseed plant. The problem of grain marketing had been solved earlier by the establishment of a flour mill, while that of storage had resulted in the construction of rail-side grain elevators. Other needs of the growing farm community were provided for by a small foundry, a machine and metal works which shipped in basic materials by rail either for processing or assembling. Domestic demands, also, attracted a widening range of trade, business and commercial enterprises to the city centre.

Added incentives to industrial enterprise included free sites offered by the city to any industry employing a reasonable labour force. The municipality owned its own utilities, to the advantage of the domestic consumer, and was prepared to charge very low rates for natural gas fuel used by industry. Electricity was also available at an early date, and an indirect concession was introduced to keep the rates low for the industrialists. In an unusual effort to attract labour the municipality built over 300 homes prior to 1914, and offered them at comparatively low rentals.

By mid-1912 the local papers could report that the largest factory in town, owned by the Alberta Clay products, employed 200 men. The Medicine Hat Porcelain Manufacturing Company, which in this same year had just begun operations, employed 55 men. Although a single flax and flour mill had already employed 25 men, the nationally-important Ogilvie Flour mills were already committed to building and operating a large flour mill on the south

side of the town. At this date also, 100-150 men were employed in a small foundry and machine rolling mill company, producing flat iron sheets, bar iron, iron pipes, castings and machines. Aside from the railway, the only other important concern was the Burns Construction Company which provided jobs for another 50 men.

Other important changes were also affecting the town. Many newcomers used its facilities while in transit to their land, while other newcomers bought lots and settled in the community. Police records indicate that there was little crime during these hectic years, for most of the incomers had serious plans and the floating element was small.

At first the heaviest demand for land was in the vicinity of the railway station but, by the autumn of 1912, the settlement was about evenly divided on either side of the railway track. Males out-numbered females by 2,530 at this date – another indication of boom conditions. The influx of people soon outstripped the supply of accommodation even though there were now five hotels, and in the spring of 1913 both the municipality and the Federal Department of Immigration were supplying tents in an attempt to house the excess population. A "tent town" had again appeared, despite the fact that all the suitable buildings, including the local curling rink, had been pressed into service. The beginning of this migration coincided with the first manifestations of civic pride and the development of social amenities. By 1910 the laying of concrete pavement had just begun, 14.7 miles of water mains and 6.95 miles of sewers were completed, and one-fifth of the city's total building expenditure of $487,293 was earmarked for new public buildings.

The smaller population centres along the railway line showed a dichotomy in their development. There were those which possessed comparable mineral resources to Medicine Hat, but lagged behind in their progress, and there were those which prospered from the disposal of the available land. In the former group were Coleridge and Dunmore which had initially been dependent upon the railway, but once they had been passed over in favour of Medicine Hat they were never able to attract enough industry to compete for pride of place. They then became shipment points for agricultural products and local service centres, utilizing natural gas domestically and supplying labour for the Medicine Hat-owned clay pits. Dunmore was relocated in 1886 but, in spite of being boosted as "the Crown of the Hat," it never really recovered from the move. This became very evident when the townsite was put up for sale in 1913. By 1910 Coleridge had grown to about 300 persons and possessed at this time a small roundhouse and coal depot for the Soo-Spokane train, a post office, hotel, school and church, together with several general stores.

Though established later, Redcliff quickly acquired the basic service features of this group of settlements – the grain elevator; the foundry, smith or implement shop; the lumber yard; the hotel; the school; the church and assorted stores. However, the people showed imagination in the utilization of their local resources of natural gas, clay, and coal, and they successfully played upon their location beside the railway and river to attract several new industries. The population increased from 220 in 1911, to 1,137 in 1921. As in Medicine Hat, ceramics and horticultural enterprises soon appeared, to be followed by glass production and restricted branches of the iron and steel trade. The latter proved transitory, ceasing at the end of World War I, as did also the proposed development of industries manufacturing furniture, shoes, gloves and cigars.

In the remaining group of settlements, Seven Persons and Bowell both grew as small service centres for the incoming homesteaders, while Suffield was originally intended to become the business centre for the South Alberta Land Company's irrigation project.

By 1913 all these settlements had reached village size, with populations ranging from 200 to 500 persons. They were mainly service type centres satisfying the many common needs of a local population that possessed only limited mobility. This fact deserves emphasis because the subsequent decay or stagnation of these settlements cannot be wholly attributed to the vicissitudes of farming. The younger generation would not completely accept the views or allegiances of its elders, and as time moved on a change in outlook was inevitable. Similarly, space relationships which had developed after

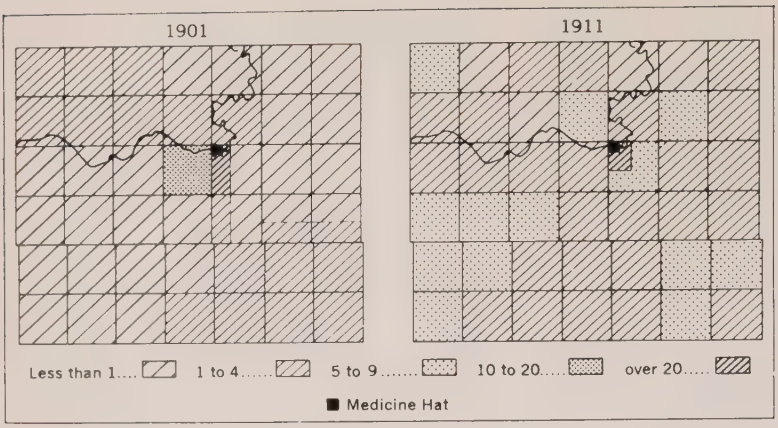


FIGURE 4
Density of settlement per square mile shown by township and quarter section.

the arrival of the railway were modified with the appearance, and later, the widespread use throughout the area of roads and automobiles.

SUMMARY

Within a period of thirty years most of the Medicine Hat area had been pioneered, producing an open settlement pattern. Momentum for population growth gained impetus with the influx of comparatively young immigrant families, the proving and utilization of local resources, effective propaganda and the services of the railway. The distribution of homesteads was generally related to distance from the railway and was not yet a function of soil, fertility or water availability. Ranches, on the other hand, were not so dependent upon haulage distances to the railway but rather upon reliable water supplies. In spite of common origins, two different kinds of agglomerated settlement had sprung up beside the railway. Only a rudimentary transportation system had yet developed on selected overland trails and near the railway track. The agricultural possibilities of the area had been fairly widely explored in this period. Crop production, however, had increased at the expense of accumulated soil fertility in marginal farmland of light texture and the outbreak of hostilities in 1914 merely delayed the day of reckoning.

Medicine Hat quickly became pre-eminent in the area, for an acceptable river front site favoured symbiosis between the settlement and the railway. Growth of the town was largely confined to the south bank of the river and consequently the problems of a river-divided settlement were not encountered in the early years nor did they become serious until later. Coal, gas and clay deposits were quickly proved and immediately made available for domestic and industrial uses. Many of the early inhabitants were already experienced in the living conditions of the Canadian West and the new settlement was therefore, competently established. As in the United States, the anticipation or development of homesteading entailed distribution functions. When the need arose for a suitable distribution centre, Medicine Hat was both the most advanced and the most convenient place available. Similarly, it benefited from the fact that the initial concentration of cultural amenities and organizations occurred here.

This period of innovation and adjustment lasted about thirty-four years, during which human activities were anticipatory while local interests predominated. The availability of quarter-sections for homesteaders implied the possibility of rural population densities ranging from 4 to 20 persons per square mile (Figure 4). It was to be followed by one of readjustment and rationalization and later, in the years after the Second World War, by one of affluence in which more carefully considered developments occurred within a provincial and national framework. The present average rural population density of 1.35 persons per square mile, is therefore, indicative of the rethinking and readjustments that took place after 1914.

ACKNOWLEDGMENTS

In addition to the many persons in southeast Alberta from whom he received assistance, the author wishes particularly to thank A. Gunter, the members of the Mitchell family and the Editor of the Medicine Hat News.

BIBLIOGRAPHY

Alberta, Industrial Development Board
1959 : *Survey of Medicine Hat.* Queen's Printer, Edmonton.

Alberta, Industrial Development Board
1959 : *Survey of Redcliff.* Queen's Printer, Edmonton.

Alberta, Department of Industries and Labour
1954 : Facts and figures on Alberta (prepared by the Alberta Bureau of Statistics). Queen's Printer, Edmonton.

Brown, A. and Morton, R.
1914 : *Twentieth century impressions of Canada.* Sells Ltd., London. (*see* 678-688).

Canada, Department of Interior (Hon. Thos. White, Minister)
1886 : *Descriptions of the townships of the North-West Territories west of the 4th and 5th initial meridians.* MacLean, Roger and Company, Ottawa. 366 p. + maps.

Canada
1952 : *Report of the Royal Commission on the South Saskatchewan River Project,* Chapters 3 and 4. Queen's Printer, Ottawa.

Common, R.
1962 : The geomorphology of the Medicine Hat area. *Geog. Bull.*, no. 18, 86-107.

Dawson, C. A.
1934 : Pioneering in the Prairie Provinces. W. Mackintosh (ed.), *Canadian Frontiers of Settlement,* v. 8, MacMillan, Toronto.

Dawson, G. M.
1885 : Report on the region in the vicinity of the Bow and Belly rivers, N.W.T. Geol. Surv. Can., Reports of Progress, 1882-83-84, Part IV, Report C.

Dempsey, H. A.
1952 : Historic sites on the province of Alberta. Department of Economic Affairs, Edmonton.

Higginbotham, J. D.
1933 : *When the West was Young.* Ryerson Press, Toronto.

McConnell, R. G.
1886 : Report on the Cypress Hills, Wood Mountains and adjacent country. Geol. Surv. Can., Reports, Vol. 1, 1885, Report C.

Manitoba Free Press
1884 : *An account of the working and results of Canadian Pacific Railway Company's Experimental farms.* Manitoba Free Press Print, Winnipeg.

Morrow, J. W.
1923 : *Early history of the Medicine Hat country.* Val Marshall Printing Ltd., Medicine Hat.

Morton, A. S.
1934 : History of Prairie settlement and Dominion lands policy. W. Mackintosh (ed.), *Canadian Frontiers of Settlement,* v. 2, MacMillan, Toronto.

Morton, W. L.
1951 : The significance of site in the settlement of the American and Canadian Wests. *Agricultural History,* v. 25, no. 3, 97-103.

Murchie, R. W.
1934 : Agricultural progress on the Prairie frontier. W. Mackintosh (ed.), *Canadian Frontiers of Settlement,* v. 5, MacMillan, Toronto.

Strange, H. G.
1954 : *A short history of Prairie agriculture.* Searle Grain Company Ltd., Winnipeg.

Wyatt, F. A. and Newton, J. D.
1926 : Soil survey of the Medicine Hat area. College of Ag., Univ. Alta., Bull. 14, Edmonton.

Items of interest relevant to the early settlement about Medicine Hat are scattered throughout old issues of the local newspapers such as the *Medicine Hat News,* the *Medicine Hat Times* and the *Lethbridge Herald.*

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 294–295, 1967

GEOGRAPHY RESEARCH GRANTS

Grants awarded by National Advisory Committee on Geographical Research for 1968-69

Anderson, D. M. Geography Carleton	User and travel analysis of the National Capital day-trip recreational zone	$ 800
Beauregard, L. Géographie Montréal	Étude géographique de l'habitat de Montréal	$2,000
Bird, J. B. Geography McGill	Slope morphology in unglaciated northwestern Canada	$1,400
Brown, W. J. Geography Manitoba	Continued quantitative studies of river cliff development and degradation in the Souris Valley	$ 550
Bryan, R. B. Geography Alberta	A study of the effect of freeze-thaw action on the formation and stability of soil aggregates	$1,800
Burton, I. Geography Toronto	Human adjustments to snow hazard	$2,000
Catchpole, A. J. W. Geography Manitoba	Prairie surface heating	$ 900
Clement, P. M. J. Géographie Sherbrooke	Recherches sur l'érosion en zone tempérée froide: exemples du Québec méridional (région de Sherbrooke)	$2,000
Dean, W. G. and Jopling, A. V. Geography Toronto	Sediment characteristics and stratigraphy of the Brampton Esker	$ 900
French, H. M. Geography Ottawa	The effects of aspect upon microclimates, soil temperatures and geomorphological processes	$1,520
Gates, G. R. Geography British Columbia	Pilot application of a control model to water resources management in a test region of British Columbia	$1,500
Gentilcore, R. L. Geography McMaster	An analysis of pioneering in Ontario	$2,000
Greer-Wootten, B. Geography McGill	Some properties of connectivity matrices	$1,000
Hewitt, K. Geography Toronto	Talus and stream entrainment of materials in a high relief basin (Canadian Rockies)	$2,400
Houde, P. Géographie Ottawa	Relations inter-régionales de l'Ouest du Québec et de l'Est de l'Ontario: analyse de flux téléphoniques	$ 800
Jackson, J. N. Geography Brock	The impact of the Welland ship canal upon land development	$2,000
Konarek, J. Geography Laurentian	Living standards in N. Ontario 1900–1960	$ 500
Mackay, J. R. Geography British Columbia	Power spectra analysis of Mackenzie Delta channels	$1,000
Macpherson, A. G. Geography Memorial	The historical demography of Newfoundland	$1,000
Manzagol, C. Géographie Montréal	Étude des facteurs de localisation des entreprises industrielles dans le grand Montréal	$1,500
Mathews, W. H. Geography British Columbia	Geographical variations in snow creep behaviour in Southern B.C.	$ 550
Maunder, W. J. Geography Victoria	The economic climatology of Canada	$1,500
McCann, S. B. Geography McMaster	Investigation of the relative roles of wave and ice action in determining beach form and plan on an Arctic environment (S.W. Devon Island, N.W.T.)	$1,600
Oke, T. R. Geography McGill	Montreal's urban heat island	$1,600
Pearson, R. E. Geography Memorial	Survey of land-use and related economic and social characteristics along a part of the Conception Bay highway near St. John's, Nfld.	$1,500
Perry, B. T. Geography Manitoba	A central place hierarchy based on hydro consumption	$1,500
Raveneau, J.-L. Géographie Laval	Établissement de cartes illustrant l'évolution de la population du Québec de 1961 à 1966, par municipalité	$1,600
Richtot, G.-G. Géographie Montréal	Les terrasses de la région de Montréal	$2,000

Ross, W. G. Geography Bishop's	Commercial whaling in Hudson Bay, 1860–1915	$ 800
Russwurm, L. H. Geography Waterloo	Geographic patterns of urban growth	$2,000
Rutherford, G. K. Geography Queen's	The chemical, physical, biological and micro-morphological characteristics of soils formed from anorthosites in Labrador with some suggestions as to their genesis	$1,000
Sandhu, K. S. Geography British Columbia	The East Indian population of British Columbia, 1904 to present	$1,380
Tyman, J. L. Geography Brandon	The occupation of western Manitoba: a case study in prairie settlement	$ 600
Wonders, W. C. Geography Alberta	Scandinavian settlement in Alberta	$1,800

GEOGRAPHICAL BULLETIN, VOL. 9, NO. 3, PP. 296-298, 1967

Book Review

TRAFFIC IN A NEW ZEALAND CITY. W. B. Johnston (Editor), Christchurch Regional Planning Authority, Christchurch, N.Z. 1965, 235 pp. Price $7.60

Fifteen years ago Christchurch was a small provincial city of less than 150,000 people. On the debit side, it had a rather dowdy core with some rapidly deteriorating housing areas; to its credit were its magnificent parks and gardens and a number of handsome suburbs. By North American standards, the city has not changed greatly since then, though the portents of future major changes are now visible. From a fleeting visit in August 1967, it was apparent that Christchurch had gained appreciably in area with the construction of low-density suburbs for the city's extra 100,000 people. Medium-rise apartment blocks and high-rise office buildings are beginning to be built in the core and there has been substantial construction of industrial and public buildings on both central and peripheral sites. Inevitably, the transportation problems which were becoming evident fifteen years ago have since been compounded.

Two factors particularly hinder the free movement of traffic in Christchurch. The first is that it is a strongly mononuclear city, with retail, office, service, industrial and storage activities all concentrated in the central area; the second, that much of the city is laid out on a grid pattern of undifferentiated streets. The grid system has proved unsatisfactory in both its orientation and its street capacities, unable to provide either efficient movement to and from the central area, easy by-pass routes, or effective links between non-central areas. A rudimentary system of radial streets does little to help because it simply increases the number of awkward and hazardous intersections on the perimeter of the central business district. As a result, scenes of confusion and congestion are commonplace, with public transport, motor vehicles, bicycles and pedestrians all competing for the right to move.

These problems have caused concern for many years and by 1967 some important steps had been taken toward their alleviation: the first stages of a motorway system were under construction and new access roads had been built through the city's outskirts. The recent volume, *Traffic in a New Zealand City*, indicates that the long-felt concern is now being directed into productive channels and that future action should be within the framework of a systematic planning policy.

Traffic in a New Zealand City is an unusual book in that it is derived from material not originally intended for publication, and was written by people not involved in the original research. In the late 1950s, the Christchurch Regional Planning Authority was given the responsibility of preparing a transportation plan for the city. This plan was presented in 1962 but the data on which it was based were not published. Apparently, the idea of publication was first raised in 1962 by W. B. Johnston, then Reader in Geography and now Professor at the University of Canterbury. As editor and co-author of *Traffic in a New Zealand City* he secured the assistance of three university colleagues, L. J. King and R. G. Golledge of the Department of Geography and A. Williman, Senior Lecturer in Civil Engineering.

The Regional Planning Authority decided to support the publication firstly, to make the bases of the Transportation Plan known to the citizens of Christchurch, and secondly, to provide, for a wider professional audience, a record of the analytical processes involved. These are difficult targets to score on at the same time, and must have caused a considerable amount of editorial torment. In Professor Johnston's words, the book was to be "neither a summary for popular consumption nor a technical

manual," but something which would appeal to lay and professional audiences alike. As a reviewer with a professional interest in cities, I find it difficult to know how to evaluate a work with such disparate objectives. It is easy to point to sections which are little more than statements of the obvious or where important analytical steps have been glossed over too lightly, but it is hard to refute the argument that such treatment may be necessary for lay readers.

Another problem for the reviewer arises from the source of the data upon which the book is based. In the editor's words, the authors received a "mass of material" from the Regional Planning Authority in "various degrees of digestion". Some of this material is included in appendices, but the reader has no way of knowing how complete a record these provide nor what selection process was involved. Nor do the authors provide any evaluation of the data presented to them. The reader, then, has no way of knowing if analytical deficiencies are the result of inadequate data, improper analysis or editorial misdirection. A related difficulty is that it is not at all clear how much of the interpretation of data is the authors' own, and how much results from conclusions reached by the planners. For all these reasons, it seems fairer to view the work as a technical rather than a scholarly production, and I am sure that the authors would not wish it otherwise. For these reasons, too, the following remarks are more in the nature of a commentary than a critical evaluation.

The book contains seven chapters in an eminently logical arrangement. In the first, "Towards the Future", Johnston outlines the Christchurch traffic problems and the purpose and format of the study. In "Land Use in Christchurch", the first main chapter, King begins with brief, straightforward descriptions of the physical setting, the past growth, and the 1959 distribution of land uses and continues with a slightly more analytical discussion of intensity of use as measured by land use percentages, population density, household size, residential property values, and employment. The main strength of this section lies in the accompanying series of maps showing the various intensity measures plotted through a mesh of sub-sectors which were delimited to contain approximately one thousand households each and which formed the spatial base for data collection and analysis. It is presumably a reflection of the dualism of editorial policy that more space was not given to the development of a meaningful analysis of the data recorded in these maps.

Golledge's contribution, "Travel and Traffic 1959", is a background chapter explaining the various transportation survey techniques used and summarizing the principal patterns disclosed. The original surveys followed standard procedures and appear to have been most conscientiously and comprehensively conducted. The sheer volume of information could not have made it easy for Golledge to arrive at a meaningful and reasonably brief summary. He discusses city-wide patterns under such headings as vehicle ratios; mode, purpose and time of travel; parking; and types of trips. He continues with a more detailed and therefore more informative analysis of traffic movements to and from the central traffic district, the suburbs and external areas – particularly the Port of Lyttelton. In an attempt to relate traffic patterns to the land use and other patterns discussed by King, the chapter concludes with a word on trip generation. Through statistical testing, it is concluded that, of the many variables contributing to traffic generation, four are particularly significant to Christchurch: average valuation of residential improvements; total employment; commercial employment in defined shopping centres; distance from the city centre.

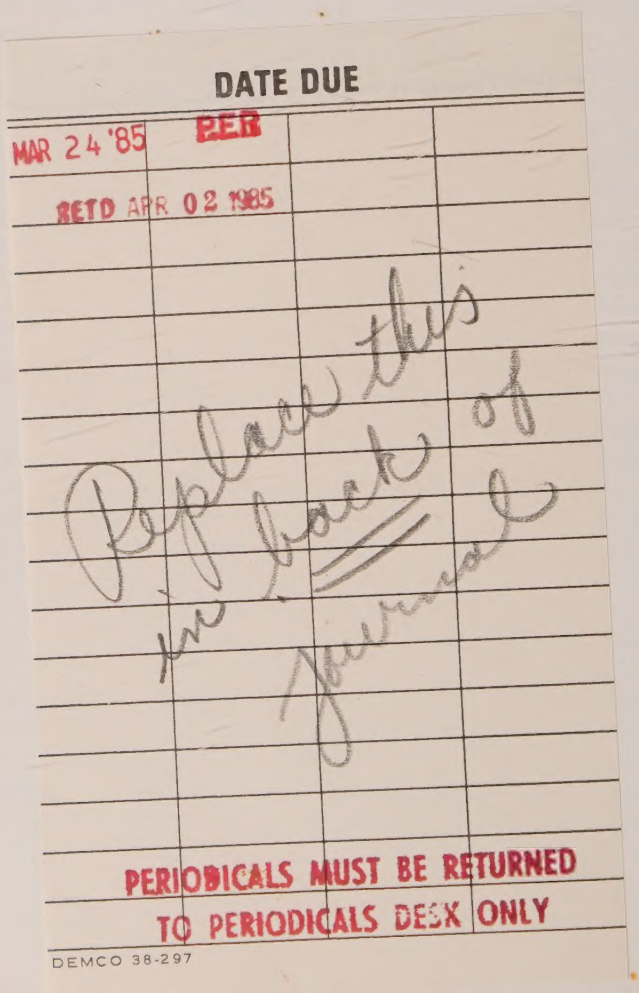
With the basic patterns established, the work moves into the phase of projection with Johnston's chapter on "Population and Economic Growth" and Williman's two chapters, "Estimating Future Travel" and "The Traffic of 1980". The projection of transportation needs was based on a population estimate of about 350,000 for 1980. The explanation of how this estimate was arrived at and how it was used to predict patterns and trends with transportation significance is rather incomplete. With commendable logic and consistency, the projections are built on the base data of 1959, using the same division of the city into subsectors and emphasizing the four primary variables identified in Golledge's chapter. Johnston also takes account of another variable

– the changing patterns of motor vehicle ownership and use.

Williman's first chapter, the most technical in the book, is concerned with the means by which formulae for trip prediction were developed. It culminates in a series of maps showing 1980 *desire lines* for a variety of types of travel. In the final chapter Williman shows how these *desire lines* are assigned to actual routes and destinations, and brings out their significance in terms of street loads and capacities, parking needs, and the construction of new traffic facilities.

There can be no doubt that the publication of *Traffic in a New Zealand City* was a worthwhile venture. Whether or not it was done in the most successful way, I cannot judge for my professional involvement is too great and my professional predilections too strongly entrenched for me to be sure of a balanced view. In one important respect the book is an unmistakable success. It is a most handsome volume, printed on art paper in a large format and copiously and effectively illustrated. The large number of coloured maps are particularly fine, and it is a minor quibble that superimposed lines do not always match the corresponding lines of the base map. Photographs are generally well handled, though some of them suffer from rather amateurish composition and reproduction. The over-all effect is extremely pleasing.

P. J. Smith


DATE DUE
MAR 24 '85 PER
RETD APR 02 1985
Replace this in back of journal
PERIODICALS MUST BE RETURNED
TO PERIODICALS DESK ONLY
DEMCO 38-297